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2017 Coastal Master Plan

Appendix C: Modeling

Chapter 3 - Modeling Components and Overview

Report: Version III

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties, and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement, and enforce a comprehensive coastal protection and restoration master plan.

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Executive Summary

Coastal Louisiana has experienced dramatic land loss since at least the 1930's. A combination of natural processes and human activities has resulted in the loss of over 1,880 square miles since the 1930's and a current land loss rate of 16.6 square miles per year. Not only has this land loss resulted in increased environmental, economic, and social vulnerability, but these vulnerabilities have been compounded by multiple disasters, including hurricanes, river floods, and the 2010 Deepwater Horizon oil spill, all of which have had a significant impact on the coastal communities in Louisiana and other Gulf coast states. To address this crisis the 2007 Coastal Master Plan was developed under the direction of the Louisiana Legislature. 2012 marked the first five-year update to the plan, and the second update is scheduled for 2017.

An overview of improvements made to the modeling tools since 2012, including descriptions of entirely new subroutines and/or processes is provided in Chapter 3. One of the most substantial improvements is the integration of previously disparate models (eco-hydrology, vegetation, wetland morphology, and barrier islands) into an Integrated Compartment Model (ICM). Spatial resolution was increased in the hydrology and morphology subroutines, hydrology compartment configuration was improved, sediment distribution was refined to more accurately capture coastal processes, and marsh edge erosion is now included. The vegetation model has new types of species, including forested wetlands, dune and swale species, and improvements to floating marsh. The vegetation subroutine also improved the dispersal function and establishment and mortality tables, upon which species can become established or lost over time. The barrier island model now includes breaching, overwash/cross-shore profile change, back barrier marsh, wave transformation, and the ability to incorporate explicit storm effects. Hydrology, water quality, and landscape input data sets were updated for use in this modeling effort, and a 50 year record of tropical storms was developed. A number of the habitat suitability indices used in 2012 were revised and others were developed for use in the 2017 modeling effort. Statistical analysis was used to improve HSIs rigor, and they were coded into the ICM. Unlike in 2012, the 2017 Coastal Master Plan modeling effort includes a community fish and shellfish model (Ecopath with Ecosim [EwE]). Lastly improvements were made for storm surge and wave modeling and for risk assessment modeling (CLARA). Improvements include expanded spatial coverage, updated input data, improved internal calculations, and a parametric uncertainty analysis for more insight into the uncertainties associated with the predictions.

Additional details for the modeling components are provided in a series of attachments.

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List of Abbreviations

AA	Atchafalaya-Terrebonne
ADCIRC	Advanced Circulation
AEP	Annual Exceedance Probabilities
ALG	Blue-Green Algae
BIMODE	Barrier Island Model
BLH	Bottom Land Hardwood
C	Habitat Capacity
CIMS	Coastal Information Management System
CLARA	Coastal Louisiana Risk Assessment
CLEAR	Coastal Louisiana Ecosystem Assessment And Restoration
CP	Chenier Plain
CPRA	Coastal Protection And Restoration Authority
CPUE	Catch Per Unit Effort
CRMS	Coastwide Reference Monitoring System
CV	Coefficient Of Variation
DEM	Digital Elevation Model
DET	Detritus
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
EAD	Expected Annual Damage
EwE	Ecopath With Ecosim
F	Fishing Mortality Rates
FEMA	Federal Emergency Management Agency
FWOA	Future Without Action

GIS	Geographic Information Systems
HSDRRS	Hurricane and Storm Damage Risk Reduction System
HSI	Habitat Suitability Index
HURDAT	HURricane DATabases
ICM	Integrated Compartment Model
JPM-OS	Joint Probability Method With Optimal Sampling
LACPR	Louisiana Coastal Protection and Restoration
LDEQ	Louisiana Department of Environmental Quality
LULC	Land Use and Land Cover
MPData Server	Master Plan Data Server
MTTG	Morganza To The Gulf
NARR	North American Regional Reanalysis
NCDC	National Climatic Data Center
NOAA	National Oceanic And Atmospheric Administration
NODC	National Oceanographic Data Center
OECLs	Oyster Environmental Capacity Layers
PB	Pontchartrain-Barataria
PM-TAC	Predictive Models Technical Advisory Committee
QA/QC	Quality Assurance And Control
RAID	Redundant Array Of Independent Disks
RSP	Regularly-Spaced Points
SAL	Salinity
SAV	Submerged Aquatic Vegetation
SBEACH	Storm Induced Beach Change Model
sFTP	Secure File Transfer Server
SSA	Spatial Statistical Approach

SWAN	Simulating Waves Nearshore
TCEQ	Texas Commission On Environmental Quality
TIP	Total Inorganic Phosphorus
TMP	Water Temperature
TN	Total Nitrogen
TSS	Total Suspended Solids
UnSWAN	Unstructured Simulating Waves Nearshore
USACE	U.S. Army Corp Of Engineers
USGS	U.S. Geological Survey
WIS	Wave Information Studies
WLV	Water Level Variability
WOD	World Ocean Database

Chapter 3: Modeling Overview

This chapter provides an overview of the modeling tools used to inform the development of the 2017 Coastal Master Plan. Contents include:

- Summary overviews of subroutines that make up the Integrated Compartment Model (ICM), focusing on major changes since the 2012 Coastal Master Plan modeling effort. ICM subroutines include:
  - Hydrology
  - Morphology
  - Barrier islands (BIMODE)
  - Vegetation
  - Habitat suitability indices (HSIs)
- Updates to the boundary conditions used for hydrodynamics, landscape, and explicit tropical storm events
- Other models utilized in the 2017 Coastal Master Plan modeling effort, including:
  - Ecopath with Ecosim (EwE) for dynamic fish and shellfish community modeling
  - ADCIRC for tropical storm surge and waves
  - Coastal Louisiana Risk Assessment (CLARA) model for assessing risk and potential damage from tropical storms
- An overview of the ICM calibration procedure
- An overview of the 2017 Coastal Master Plan data management strategy

1.0 Overview of the Integrated Compartment Model (ICM)

The Integrated Compartment Model (ICM) is a computationally efficient, coast wide mass balance model that can be used for a large number of 50-year simulations in a reasonable timeframe. It combines the previously independent models (eco-hydrology, wetland morphology, barrier shoreline morphology, and vegetation) used in the 2012 Coastal Master Plan (see Chapter 1 and CPRA, 2012 – Appendix D), and includes a number of physically-based improvements. Integrating individual models removed the inefficiency of manual data hand-offs required during the 2012 Coastal Master Plan effort (due to independent models with no internal linkages) and the potential human error that may occur during the transfer of information from one model to another. The ICM serves as the central modeling platform for the 2017 Coastal Master Plan to analyze the landscape performance of individual projects and alternatives (groups of projects) for a variety of future environmental scenarios for up to 50 years. Hydrodynamics, morphology, and vegetation are now dynamically linked with annual feedbacks. Information transfer between models was only possible at year 25 during the 2012 effort. This led to an inability of one 2012 model (e.g., vegetation) to reflect change in shorter-term processes arising from changes in related parameters projected by another model (e.g., morphology). For example, in 2012 the morphology and vegetation subroutines only exchanged information at year 25, if an area converted to a more saline tolerant vegetation type between model years 25 and 50 in the vegetation model, the morphology model was unaware of this transition. Consequently, it may have forecast the collapse of fresh marsh areas that would have converted to another vegetation type, thereby overestimating coastal wetland loss. The increased frequency in data exchange among ICM subroutines reduces those types of errors and improves the quality of model results.

Key ICM outputs include hydrodynamic variables (e.g., salinity and water level), water quality (e.g., total suspended solids [TSS] and nitrate [NO3]), changes in the landscape (e.g., land area and elevation change, including the barrier islands), and changes in vegetation (e.g., location and type). Nineteen new or improved habitat suitability indices (HSIs) have also been integrated into the ICM; however, they are considered terminal outputs as there are no feedbacks to the other ICM subroutines.

2.0 Hydrology Subroutine

The 2017 Coastal Master Plan hydrology subroutine of the ICM is a mass balance compartment model used to predict water level, salinity, sediment, and other water quality constituents for 50 years into the future. It is integrated with feedbacks to the morphology and vegetation subroutine. The 2017 hydrology subroutine was built upon the 2012 Coastal Master Plan eco-hydrology model. The spatial resolution of the compartments was increased and new processes were developed and included. The following is a brief summary of key changes since 2012. For additional details regarding this subroutine and how it is integrated into the ICM, refer to Attachment C3-1 – Sediment Distribution and Attachment C3-22 – ICM Integration.

2.1 Model Design

The 2012 eco-hydrology modeling used a mass balance approach whereby the system is characterized using a set of compartments connected by links that control the flow of constituents among the compartments. Specifically, three mass balance, link node, compartment models (Meselhe et al., 2013) were used covering different regions of the coast: (1) Atchafalaya-Terrebonne (AA), (2) Chenier Plain (CP), and (3) Pontchartrain-Barataria (PB) (Figure 10). The PB model was developed in the Formula Translating (Fortran) system programming language using the multi-type compartment design that subdivides a hydrological compartment into upland, marsh, and open water subcompartments. The AA and CP models were developed in the Berkeley Madonna equation solver governed by the same hydrodynamic equations but using the single-type compartment design, whereby a compartment is composed of only a channel, marsh, or open water rather than being subdivided (Meselhe et al., 2012). Figure 11 shows a schematic of the multi-type and single-type compartment designs. Considering the timeline for model development for the 2012 coastal master plan, existing models were used where available (e.g., PB). Although there were differences among the models used for different parts of the coast, they were standardized to the extent possible, and any differences were determined to be negligible in terms of producing 50 year model outputs. The 2017 hydrology subroutine adopted the PB Fortran multi-type compartment design. Fortran was used for the 2017 effort because it is a more flexible coding language with more versatility for integrating model code when compared to Berkeley

Madonna. The PB multi-type compartment set up was chosen over that used in the AA and CP regions of 2012 because PB was already coded in Fortran.

The new hydrology subroutine was developed as a single coast wide model (Figure 12) but can be subdivided into the AA, CP, and/or PB regions if only one or two of the regions are required for a particular simulation. Since the 2017 hydrology subroutine has adopted the PB region's design, only the differences in 2017 hydrology subroutine, compared to 2012 eco-hydrology model, are discussed in this overview.

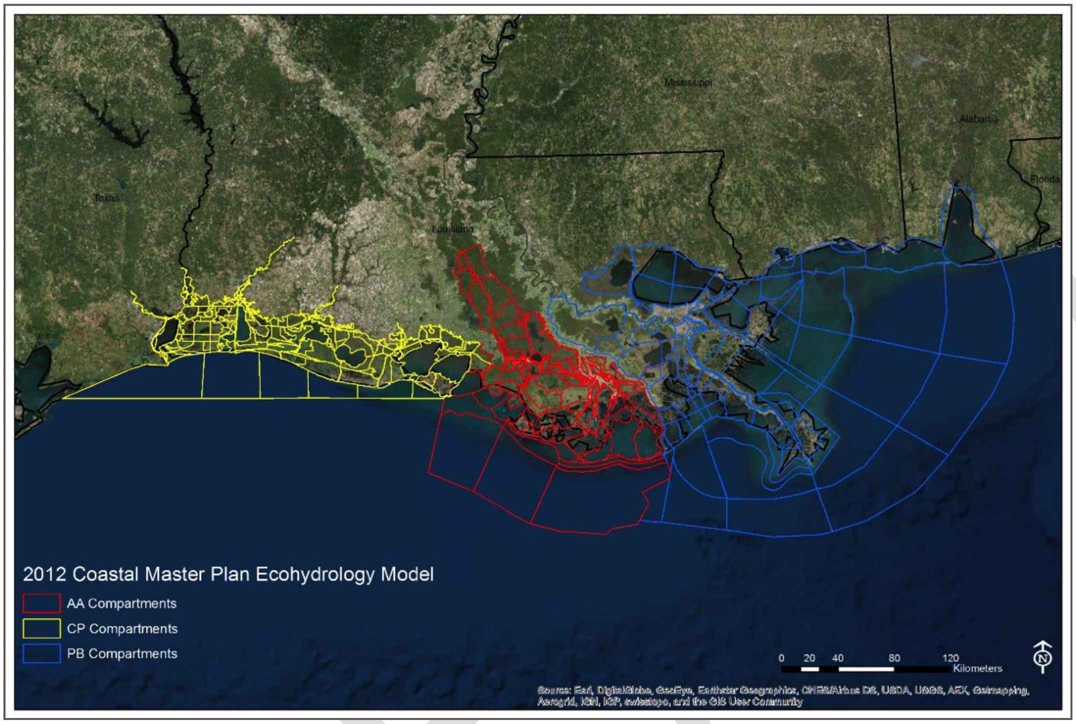

Figure 1: 2012 Coastal Master Plan eco-hydrology model compartments and domains.

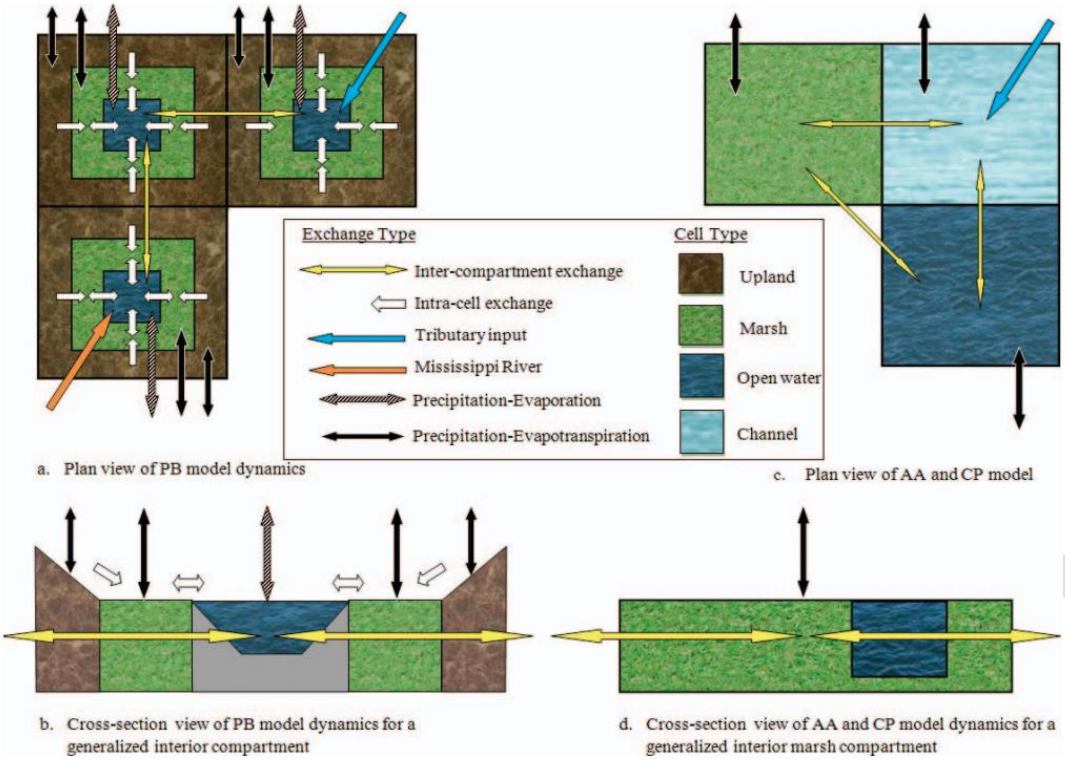

Figure 2: Multi-type (left) and single-type (right) compartment designs.

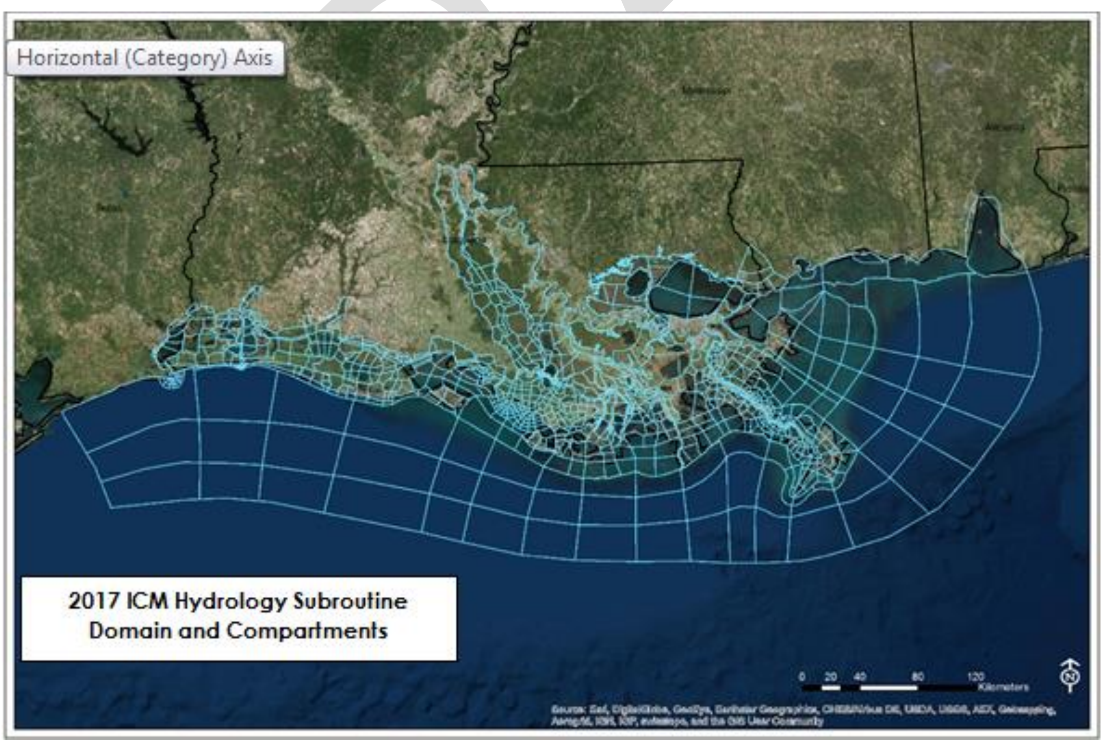

Figure 3: 2017 Coastal Master Plan Integrated Compartment Model (ICM) – hydrology subroutine compartments and domain.

2.2 Model Domain

For 2017, the southern boundary of the model domain was shifted further offshore to approximately the 30 m contour to reduce variation in salinity so a constant offshore boundary salinity could be applied and to have all the regions the same "distance" offshore. The east and west boundaries had negligible change, and the northern boundary in the AA region was shifted north to include the entire Atchafalaya Basin area between the East Atchafalaya Basin Levee and the West Mississippi River and Tributaries Levee. See Figure 10 and Figure 12 for the spatial extent of each model domain.

2.3 Compartments

Spatial resolution of the compartments in all three regions was increased compared to the 2012 effort to better represent coastal processes, such as sediment distribution (Table 11). This was made possible due to advances in computational processing power. Uncertainty in sediment distribution dynamics increases as the size of the hydrology compartments increase. Excluding large offshore hydrology compartments (which are included in Table 11), compartments specifically in the area of the modeling domain in which most diversions are modeled were reduced from an average size of 180 km^2 in the 2012 effort to 20 km^2 for the 2017 effort. It is in these compartments that accurate sediment distribution is most critical for predicting project benefits. The increased spatial resolution in these areas enhances accuracy associated with projected diversion land area benefits

Compartments in the AA and CP regions were delineated to convert them from the single-type to the multi-type compartment design. Unlike the 2012 eco-hydrology model, the 2017 hydrology subroutine now has coast wide coverage of multi-type compartments. Overall, there are a total of 946 compartments across the coast in the 2017 hydrology subroutine, compared to 403 in the 2012 eco-hydrology model.

Table 1: Summary of hydrology compartments per region and model; values include all compartments in the model domain, including large offshore compartments.

Region	2012 Eco-hydrology Model		2017 ICM Hydrology Subroutine	
	Total	**Area Ranges in km^2 (average)**	**Total**	**Area Ranges in km^2 (average)**
AA	165	0.04 – 3361 (121)	388	1.02 – 1477 (69)
CP	149	0.44 – 1844 (86)	245	0.40 – 2833 (123)[1]
PB	89	2.2 – 5844 (716)	313	1.84 – 3187 (160)

1 average area increased as a result of the additional, large offshore compartments for the CP region

2.4 Link Network

The ICM's hydrology subroutine utilizes a link-node type of hydraulic exchange. Each node of the subroutine is a hydrologic compartment, which consists of open water, marsh, and (optionally) upland areas. The links represent the hydraulic pathways (bayous, bay inlets, canals, marsh areas, etc.) connecting each compartment to neighboring compartments. All modeled processes (rainfall/runoff, sediment distribution, water quality sources/sinks, wave generation, etc.) take place within the node/compartment, and the link network is used to convey flows and constituents between compartments.

Both the 2012 eco-hydrology model and the 2017 hydrology subroutine link networks consist of intracompartmental and intercompartmental link types. The intracompartmental link types used in the 2017 hydrology subroutine consist of rainfall/runoff processes in upland, marsh, and open water areas, as well as exchange flow between the open water and marsh areas within a compartment. Of the intercompartmental link types, both the 2012 and 2017 versions include channel, lock, saltwater barrier or tide gate, and pump link types. The 2017 hydrology subroutine additionally includes weir; orifice, culvert, or bridge; overland marsh; ridge or levee; and dormant link types. Dormant links are inactive links in the model that become activated only after certain criteria are met during the model simulation. Intercompartmental links connect the open water portion of one compartment to the open water portion of a neighboring compartment, with the exception of the overland marsh links. Overland marsh links allow for overland flow across marsh areas, and connect the marsh area of one compartment to the marsh area of a neighboring compartment.

Although both 2012 and 2017 versions include lock link types, there was an update to the lock operations in 2017. The 2012 eco-hydrology model lock operations were either operated based on the recorded schedule, or not operated and remained open 100% of the time. The 2017 hydrology subroutine can operate locks based on differential stage, hourly schedule, downstream stage, downstream salinity, or downstream stage and salinity.

In addition to the hydraulic control rules that can now be simulated via the aforementioned operational regimes; weirs, orifices, culverts, and tide gates were also added to better represent the highly engineered hydrology of Coastal Louisiana within the ICM's hydrology subroutine.

Overland marsh and ridge or levee link types were added to the 2017 hydrology subroutine to allow for the propagation of extreme water levels during a major riverine flood and/or tropical system's storm surge.

Dormant links allow the building of a delta or breaching of a barrier island. For deltas, they were added to the fan-like compartment layouts in areas of actively growing deltas and areas of potential delta growth (e.g., from sediment diversion projects). As sediment is deposited and accumulates on a compartment bed, the open water link invert elevation increases, resulting in a decrease of the link's flow capacity (i.e., cross-sectional area). Once the capacity of the open water link is reduced to be equal to the capacity of the regime channel (i.e., the minimum cross-sectional area required to facilitate the specified diversion flow rate and particle size), the original open water link is deactivated and the dormant link – with dimensions of the regime channel – is activated. Additionally, sediment deposition will no longer occur in this compartment and is instead pushed downstream to the next compartment. For barrier islands, a dormant link is added to each island to be activated if an island breach occurs, forming an inlet and allowing exchange of water from offshore to the bay.

2.5 Compartment and Link Attributes

The 2012 eco-hydrology compartment bed elevations and link invert elevations were calculated using the Digital Elevation Model (DEM) developed by United States Geological Survey (USGS) for the 2012 Coastal Master Plan. The 2017 hydrology subroutine compartment bed elevations and link invert elevations were calculated using the updated 2017 Coastal Master Plan DEM. For additional information about this DEM, please refer to Attachment C3-27 – Landscape Data.

For additional information regarding compartment delineations and hydrodynamic links, refer to Attachment C3-22 – ICM Integration.

2.6 Governing Equations

The hydrodynamic formulations used in the 2017 hydrology subroutine are unchanged from 2012 eco-hydrology, as these were based on well-known and widely accepted hydrodynamic principles. These formulations can be found in the 2012 Coastal Master Plan report Appendix D-1 (Meselhe et al., 2012).

An extensive effort to improve the simulation of sediment distribution among and within hydrology compartments was undertaken for 2017. In 2012, a single sediment accumulation value was calculated for each compartment, and sediment was distributed within a compartment based on a sediment distribution probability surface, which was based upon the weighting of factors such as distance from sediment source, frequency of inundation, and distance from water bodies. Also, the 2012 eco-hydrology model assumed that open water bottoms (i.e., the bed) have an endless supply of sediment for resuspension, while the 2017 hydrology subroutine assumes a maximum TSS concentration and a limit to the amount of erodible material available for resuspension. In both the 2012 PB eco-hydrology model and the 2017 hydrology subroutine, the intracompartment exchange between the open water and marsh allowed sediment transfer to the marsh surface. In the 2017 modeling effort, an additional source of sediment (from marsh edge erosion) is included in the morphology subroutine; refer to the morphology section below for additional information.

Both the 2012 and 2017 versions of the model code distribute sediment throughout the model domain to account for tropical storms. The 2012 eco-hydrology model did not simulate tropical storms explicitly, and therefore, to schematize the process of sediment distribution from tropical events to the landscape, 1000 g/m^2/year of sediment was assumed delivered to each hydrology compartment (Couvillion et al., 2013) for the duration of the model run. The 2017 hydrology subroutine explicitly simulates tropical storm events by applying elevated water levels (i.e., storm surge) at the offshore boundary and the storm's wind field temporally and spatially along the storm's path. Therefore, the sediment from tropical storms is delivered from the offshore compartments to the marsh as sediment is resuspended from the bed due to higher wave energy, and the marsh is inundated due to higher water levels.

The 2017 Coastal Master Plan water quality constituents are predicted as part of the hydrology subroutine. The predictions are based on advection-diffusion equations of chemical species. Source/sink terms are included to account for mass transfers due to chemical kinetic processes. Water quality parameters, including total suspended solids (TSS), salinity (SAL), water temperature (TMP), nitrate + nitrite nitrogen (NO3), ammonium nitrogen (NH4), total inorganic phosphorus (TIP), dissolved organic phosphorus (DOP), dissolved organic nitrogen (DON), blue-green algae (ALG), detritus (DET) are simulated. The ICM water quality formulations are unchanged from the 2012 Coastal Master Plan AA and CP regional models. These formulations can be found in the 2012 Coastal Master Plan report Appendix D-1 (Meselhe et al., 2012).

3.0 Morphology

The 2017 morphology subroutine tracks relative elevation and uses the elevation (accretion), along with water level and salinities from the hydrology subroutine to assess changes in wetland area. The fate of a particular area of land is partly determined by its ability to maintain or build to an elevation (relative to water level) suitable for wetland vegetation establishment or persistence under varying scenarios of sea level rise, subsidence and restoration efforts.

The 2017 morphology subroutine builds upon portions of the 2012 Coastal Master Plan wetland morphology model (Couvillion et al., 2013). Improvements include a number of refinements to the coding and integration with the hydrology and vegetation subroutines in the ICM. The 2017 morphology subroutine makes projections at the 30 m x 30 m grid cell resolution of wetland area, landscape configuration, vertical accretion and elevation, compared to 500 m x 500 m which was used in 2012. As the output of this subroutine includes land area change, which is critical to the formulation of restoration and protection planning, its accuracy is of high importance. Understanding the changes that have been made to the data layers and processes since the 2012 Coastal Master Plan version of the model is also important for understanding the modeling results.

The baseline datasets were updated for the 2017 modeling effort. The 2012 models were initialized with datasets from a circa 2010 base period. The coastal landscape has changed since 2010 due to ongoing coastal process such as wetland loss, gain, and coastal restoration and protection efforts. Therefore, several input datasets were updated to reflect a 2014 starting period for the 2017 Coastal Master Plan effort. These include a late 2014 (November) land and water composition configuration dataset. The integrated bathymetry/topography dataset and the base vegetation distribution layer used for model initialization were also updated. These updated layers ensure that any changes that have taken place between 2010 and 2014, including coastal restoration projects, are appropriately considered in the model runs.

Regarding model processes, one of the least robust aspects of the 2012 modeling effort was the sediment distribution. To improve this, a number of changes were made as described in the hydrology subroutine section, and an extensive literature review was conducted and alternative methodologies considered. In addition to the changes detailed above, sediment accumulation is now calculated in three distinct zones: marsh edge, interior marsh, and open water. Sediment accumulation is also now calculated for sand, silt, and clay separately. Resuspension for silt and clay is calculated based on excess bed shear (bed shear minus critical shear) and consolidation time. The flocculation of clay is a function of the salinity. The sand accumulation rate in open water is calculated based on the difference between the sand inflow and the sand transport capacity. The flow exchange between the open water and the marshes is calculated using the Kadlec-Knight formula, in which flow is a function of vegetation density, width of the flow path, inundation depth, and the distance between stage locations. Finally, resuspension of sediment in the marshes does not occur under non-tropical storm conditions as per Christiansen et al., (2000). All of these improvements serve to reduce uncertainties in the model outputs that were previously attributed to an inability to realistically distribute sediment within a hydrology compartment.

Another important improvement that has been incorporated in the 2017 Coastal Master Plan modeling effort is the inclusion of marsh edge erosion. In 2012, marsh edge and shoreline erosion was not directly calculated, but was rather incorporated through the use of a background change rate calculated from historical land change data. Losses due to erosion were forced upon the landscape through the use of an erosion probability surface and a background land change incorporation sub-model. For the 2017 effort, spatially variable erosion rates were calculated for all shorelines that experienced erosion during a 2004-2012 observation period. The morphology subroutine calculates the number of pixels of shoreline that should be eroded for any given modeling period based upon these historical rates. Those areas are then converted from land to open water in the ICM. These spatially variable rates, calculated from high resolution historical imagery represent an improvement from the background change rate method previously used.

For additional information on how the morphology subroutine is integrated in the ICM, refer to Attachment C3-22 – ICM Integration.

4.0 Barrier Islands (BIMODE)

This section summarizes the changes made in the Barrier Island Model (BIMODE) subroutines between the 2012 and 2017 Coastal Master Plan modeling efforts. The 2012 version is documented in Appendix D-3: Barrier Shoreline Morphology Technical Report (Hughes et al., 2012), and a more complete description of the 2017 version of BIMODE is provided in Attachment C3-4 – Barrier Island Model Development (BIMODE).

In general, BIMODE is a planning level model separated into six island regions: Isles Dernieres, Timbalier, Caminada Headland and Grand Isle, Barataria, Breton Island, and Chandeleur Island. It is capable of predicting barrier island evolution for 50 years. It is physically based and includes both long-shore and cross-shore processes and has the ability to explicitly capture the effects of tropical storm events on overwash. BIMODE interacts with other ICM subroutines, including dune, swale, and back barrier marsh vegetation from the vegetation subroutine, erosion of back barrier marsh area via the morphology subroutine, and hydrodynamic exchange through tidal inlets from the hydrology subroutine.

Below are specific comparisons of the 2017 BIMODE and the 2012 barrier shoreline morphology model.

4.1 Model Language

The 2012 model was coded using Matlab ver. 2010. The 2017 BIMODE source code was written using Fortran 90. This change was selected by the modeling team to increase model speed and to facilitate merging it with the other subroutines of the ICM.

4.2 Wave Input and Transformation

The 2012 model effort used 20 years (1989 – 2009) of Wave Information Studies (WIS) data (Hubertz and Brooks, 1992). The WIS data was integrated into annual average data using wave height and direction bins (Hughes et al., 2012). This provided 20 sets of wave height and direction per WIS location to drive long-shore transport. The sequence was repeated 2.5 times to provide a 50-year wave series. Ten WIS locations were used to develop the wave climate; three on the east side of the Mississippi River and seven on the west side of the Mississippi River. The 2017 modeling effort used 32 years of WIS data (1980-2012) to develop wave statistics and input. The 2017 subroutine developed monthly average wave height, period, and direction data from the WIS dataset. This provided 384 different sets of wave height and direction per WIS location. Six WIS locations were used as inputs into the model; two on the east side of the Mississippi River and four on the west side of the Mississippi River.

The 2012 model used the wave angle at the WIS station and the shoreline angle to drive long-shore sediment transport and a simple shoaling algorithm was used to address changes in wave height. The 2017 modeling effort used the Simulating Waves Nearshore (SWAN) model to transform the waves from the WIS station to the – 4 m contour. This allowed for wave refraction, shoaling, breaking, damping, etc., from the offshore wave location to a location closer to shore.

The 2012 model effort smoothed the wave angle at each time-step (i.e., annually) when calculating long-shore transport. The extent of smoothing was based on the island width and shoreline length and used between one and three smoothing passes. The 2017 model smoothed the wave angle over 1,500 m and used a "staggered smooth" for profiles within 1,500 m of the end of a littoral cell. This involved using fewer profiles for the smoothing when within 1,500 m of the end of the littoral cell.

4.3 Cross-shore Response

The 2012 model did not include a cross-shore response due to tropical storm events. The 2017 version includes a cross-shore response by incorporating output from the Storm Induced Beach Change Model (SBEACH). The BIMODE subroutine selects the SBEACH profile that most closely resembles the BIMODE profile and applies the change between the input and output SBEACH profiles to the BIMODE profile. Thus, the lowering and overwash of the profile due to tropical storms is included in the 2017 model.

4.4 Shoreline Smoothing

The 2012 model smoothed the shoreline location across five adjacent profiles. A fixed cross-shore shape was assumed. The 2017 BIMODE code did not include shoreline smoothing because the shape of the cross-shore profile was revised using SBEACH.

4.5 Breaching

The 2012 model did not include criteria for the initiation of breaching. The 2017 subroutine includes several criteria for the development of breaches within an island chain including minimum island width, ratio of distance of the potential breach from the end of the island, and breach width-to-length ratio. Breaches are provided as feedback into the ICM as a way to capture hydrodynamic changes that may affect other subroutines.

4.6 Bay Feedback Frequency

Considering the timing for model feedbacks, the 2012 model only provided the cross-sectional area for an inlet every 25 years. The 2017 version of the model provides this on an annual basis.

4.7 Marsh Impacts

The 2012 barrier island model included a marsh accretion formula. For 2017, this is captured as part of the wetland morphology subroutine. The 2012 model did not include bayside marsh recession. A constant value – based on historic marsh recession rates – was included in the 2017 BIMODE subroutine for areas where the bayside marsh is exposed to wave action.

4.8 Calibration

The 2012 model was calibrated using shoreline changes between 1989 and 2009-2010. The 2017 model was calibrated using data from January 2006-December 2014.

5.0 Vegetation

The vegetation subroutine is a coast wide model integrated into the ICM and predicts changes in coastal vegetation types and coverage. It is directly linked to the hydrology and morphology subroutines. The update of the vegetation subroutine (LAVegMod 2.0) for the 2017 Coastal Master Plan builds on the strategy used in the 2012 Vegetation Model (LAVegMod) (Visser et al., 2013). The approach characterizes each species by the range of environmental conditions that promote or inhibit the growth of individuals per 500 m x 500 m grid cells. Dynamic changes in the species composition of the community arise as environmental conditions shift from favoring one species to favoring another. The change in vegetation at a site is driven first by mortality of existing vegetation due to the current environmental conditions. The mortality is interpreted by the model as a loss of species cover at a location. The reduction in plant cover caused by mortality creates space for the establishment of other wetland plant species. Unoccupied land also can occur as a result of soil morphodynamics and the creation of new land. Establishment of a species on unoccupied area is driven by the environmental conditions during the year in which the species establishes.

Significant changes have been made for LaVegMod 2.0. These changes fall into four broad categories. First, the number of habitats covered by the model has significantly increased. A number of species not included in the previous model have been added, and habitat types that represented aggregates of several species in the previous model have been divided into individual species for the revised model (Table 12). Second, the model code has been updated to reflect species-level niche requirements and ability to colonize a new cell. Third, the model has added the effects of dispersal on community dynamics. Finally, the model code has been streamlined and converted to the Python programming language for integration into the ICM. In addition, the similarity between the outputs from the two model versions was tested using one hydrology file from the 2012 Coastal Master Plan effort.

5.1 New Vegetation Habitats and Processes

The updated vegetation subroutine includes both an increase in the number of emergent wetland species as well as the inclusion of new species that represent new habitats (Table 12). New habitats included for 2017 include dunes and swales, bottomland hardwoods, and floating marshes.

Dune and swale communities occur along very sharp gradients that are primarily driven by elevation. To help capture these sharp gradients, the vegetation team attempted to apply polygons based on 5 cm elevation contours on the barrier islands rather than the 500 m x 500 m vegetation grid cells used in other habitats; however, due to large computing requirements of the vegetation subroutine, it was not feasible to implement a finer resolution along the barrier islands, and the 500 m x 500 m vegetation grid was used. Mortality and establishment probability matrices are based on unpublished data from Dr. Mark Hester (refer to Attachment C3-5 – Vegetation) and literature on the distribution of these species in dune and swale environments. The ecology of these species is different than that of the emergent marsh species. Mortality and establishment processes for dune and swale species are most strongly influenced by elevation above the water surface, as opposed to salinity and water depth variation for the emergent marsh species. Due to time constraints during the code development phase, the barrier island algorithm does not take dispersal or spread into consideration. As bare ground becomes available when species die, it is proportionally occupied by all barrier island species based on the elevation of the polygon in the year of establishment.

Bottomland hardwood species have also been included for 2017. The ecology of these species is also distinct from that of emergent marsh species, with distribution primarily driven by their elevation relative to mean water level. In addition, similar to swamp species, bottomland hardwood species can only establish from seeds that germinate in the spring and early summer under moist (not flooded) conditions and, once germinated, seedlings cannot survive when deeply flooded. Therefore, the algorithm for these species limits establishment to periods between March 1 and July 30 in which there are two weeks when water levels are below the soil surface, followed by two weeks of water levels not greater than 10 cm above the soil surface. The mortality and establishment processes for these species and the parameterization for the associated algorithms were generated by Dr. Gary Shaffer's unpublished data (refer to Attachment C3-5 – Vegetation) for the bottomland hardwood species, as well as a review of the literature on the distribution of these species. New algorithms were added to the vegetation subroutine to reflect the distinct ecology of bottomland hardwoods.

Floating marshes occur in fresh water environments, and although numerous hypotheses regarding their ecology have been proposed, the exact mechanism for establishment of these marshes in Louisiana remains unclear. There is a quantity of information regarding the processes that lead to the demise of these habitats; therefore, the revised vegetation subroutine focuses on how these marshes are eliminated. Elimination of the floating marsh occurs when mortality of one of the floating marsh species occurs and is not replaced by the establishment of another floating marsh species. This leads to the death of the floating marsh and the conversion of the area vacated by these species to water. This information is then communicated to the ICM morphology subroutine.

5.2 Species Level Niche Requirements

Niche requirements for the emergent marsh and swamp forest species in the vegetation subroutine are based on at least 20 occurrences of the species in the Coastwide Reference Monitoring System (CRMS) data. The standard deviation of the daily mean stage (hereafter referred to as water level variability, or WLV) and average annual salinity were merged with vegetation cover data for each of the 392 CRMS sites using annual observations from 2006-2012. The weighted probability distribution – using percent cover as the weight – of the hydrology variables was then calculated for each of the species. For mortality, the center of the distribution of the species between the 25th and 75th percentile of both WLV and salinity was assigned 0% mortality. Outside of the 5th and 95th percentile of salinity, the mortality was set to 100%. Because the observed WLV is lower than the expected species tolerance, the mortality probability function was stretched so that the increase in mortality is slower as WLV increases. For establishment probabilities, the mortality matrices were inverted and shifted one model grid cell towards lower salinity and one cell towards either higher or lower WLV depending on if the species prefers lower or higher WLV. Establishment of species in a cell is determined by availability of space, the availability of species in the eight cells surrounding it, as well as those species that are in the cell, and is proportional based on the establishment probabilities of those species based on the hydrologic conditions in the year of establishment.

5.3 Dispersal

Dispersal is an important process governing the distribution of species on the landscape. The 2012 version of the code (LAVegMod) did not include the effects of dispersal, and when land became available for a species to establish either through mortality or land building, any species that matched the current environmental conditions could become established. This happened regardless of whether or not a species had representatives in the surrounding area to provide seeds or propagules. This may have resulted in unrealistic behavior in the first generation of the model. In the 2017 version (LAVegMod 2.0), algorithms that account for the ecology of plant dispersal have been incorporated. In the revised subroutine, plant species can only become established in a new area if the species is already present in the surrounding area or in the cell. Currently, the surrounding area is defined as the eight immediate 500 m x 500 m cells that surround a 500 m x 500 m cell. The result of adding dispersal is the prevention of species from appearing in unrealistic locations, as well as a more realistic pattern of species advance and retreat over the landscape as environmental conditions change.

5.4 Programming Language

In addition to revising and expanding the range of ecological phenomena captured by the model, a substantial effort has been undertaken to implement the model in Python. The previous version of LAVegMod used a combination of R and C++ code. Translation of the model into Python reduced the size (i.e., number of lines) of the code base, simplified many of the algorithms, made the subroutine easier to integrate with the overall ICM, and simplified the communication of information back and forth between ICM subroutines. Additional simplifications were also made where possible because of basic structural differences between Python and C++.

Table 2: Species and habitats included in LAVegMod 2.0.

LaVegMod Habitats	LaVegMod 2.0 Habitats	Continued Species	New Species
	Bottomland Hardwood Forest		*Quercus lyrata* Walter, *Quercus texana* Buckley *Quercus.laurifolia* Michx. *Ulmus americana* L., *Quercus nigra* L., *Quercus virginiana* Mill.
Swamp Forest	Swamp Forest	*Taxodium distichum* (L.) Rich *Nyssa aquatica* L. (these were represented together in the swamp category)	*Salix nigra* Marshall *Taxodium distichum* (L.) Rich *Nyssa aquatica* L. (each species is now represented individually)
	Fresh Floating Marsh		*Panicum hemitomon* Schult. *Eleocharis baldwinii* (Torr.) Chapm. *Hydrocotyle umbellata* L.

LaVegMod Habitats	LaVegMod 2.0 Habitats	Continued Species	New Species
Fresh Marsh	Fresh Attached Marsh	*Morella cerifera* (L.) Small *Panicum hemitomon* Schult. *Zizaniopsis miliacea* (Michx.) Döll & Asch. *Typha domingensis* Pers. *Sagittaria lancifolia L.*	*Sagittaria latifolia* Willd.
Intermediate Marsh	Intermediate Marsh	*Phragmites australis* (Cav.) Trin. ex Steud. *Schoenoplectus californicus* (C.A. Mey.) Palla	*Iva frutescens* L. *Baccharis halimifolia* L.
Brackish Marsh	Brackish Marsh	*Spartina patens* (Aiton) Muhl. *Paspalum vaginatum* Sw.	
Saline Marsh	Saline Marsh	*Juncus roemerianus* Scheele *Distichlis spicata* (L.) Greene *Spartina alterniflora* Loisel. *Avicennia germinans* (L.) L.	
	Dune		*Uniola paniculata* L. *Panicum amarum* Elliott *Sporobolus virginicus* (L.) Kunth.
	Swale		*Spartina patens* (Aiton) Muhl. *Distichlis spicata* (L.) Greene *Solidago sempervirens* L. *Strophostyles helvola* (L.) Elliott *Baccharis halimifolia* L.

6.0 Habitat Suitability Indices (HSIs) – Fish, Shellfish, and Wildlife

Habitat suitability index (HSI) models are used to generate a relative score for the condition (i.e., suitability) of an area to support a particular organism. HSI models consist of simplified relationships that relate key environmental variables to the quality of the habitat for that organism. The relationships, termed suitability indices, are standardized on a 0 to 1 scale, with 1 being the most favorable conditions and 0 being completely unsuitable. The relationships used to develop the suitability indices are often derived using literature or expert professional judgment. The suitability indices are then aggregated, often using an arithmetic or geometric mean to produce a single HSI score for the area of interest. During the aggregation procedure, variables may be weighted higher than others given their relative importance to the organism. Although HSI models are often criticized because they quantify habitat conditions, which may not directly correlate to species abundance, they remain a practical and tractable way to assess changes in habitat quality for various species.

The 2012 Coastal Master Plan utilized both existing and newly developed HSIs to evaluate potential project effects on alligator (Nyman, 2012a), crawfish (Romaire, 2012), gadwall (Leberg, 2012a), mottled duck (Leberg, 2012b), green-winged teal (Leberg, 2012c), muskrat (Nyman, 2012b), neotropical migrant birds (Leberg, 2012d), river otters (Nyman, 2012c), roseate spoonbills (Leberg, 2012e), largemouth bass (Kaller, 2012), eastern oyster (Soniat, 2012), brown shrimp (Baltz, 2012a), white shrimp (Baltz, 2012b), and spotted seatrout (Baltz, 2012c) habitat. The HSIs were reevaluated and improved for use in the 2017 modeling effort. This included reassessing the species to be modeled, the environmental variables to be included, data and information available to support the selection of variables, and the formulation of the suitability functions.

The species selected for inclusion in the 2017 Coastal Master Plan modeling effort include: mottled duck, green-winged teal, gadwall, wild-caught crawfish, alligator, brown pelican, blue crab (juvenile), brown shrimp (large and small), white shrimp (large and small), Gulf menhaden (adult and juvenile), bay anchovy (adult and juvenile), spotted sea trout (adult and juvenile), largemouth bass, and oysters. Considering there are no existing HSI models for brown pelican and blue crab, new HSIs were developed for this effort. An attempt was made to develop an HSI for blue catfish; however, this was not possible due to a lack of associated literature and/or supporting data. Similar to the 2012 effort, the 2017 HSIs are at a model grid cell resolution of 500 m x 500 m.

The HSI model improvement effort had three main focuses: (1) updates of HSI models for five wildlife species, i.e., three water fowl species (mottled duck, green-winged teal, and gadwall), wild-caught crawfish, and alligator, (2) development of new HSI models for brown pelican and blue crab, and (3) improvements of HSI models for the following fish and shellfish species: brown shrimp, white shrimp, Gulf menhaden, bay anchovy, speckled trout, largemouth bass, and oysters. The wildlife, fish, and shellfish HSI models were developed or improved upon by first identifying the life stages that should be represented in the models. Next, literature reviews were conducted to determine the key environmental variables that influence habitat quality for the selected life stages for each species of interest. For the wildlife species (i.e., waterfowl, crawfish, and alligator), outcomes of the literature reviews and expert professional judgment were used to update the existing equations or generate new suitability equations for each variable in the HSI models. For the fish and shellfish species, an additional step was taken to generate new suitability equations using existing field data from the Louisiana Department of Wildlife and Fisheries long-term fisheries-independent monitoring program. Statistical relationships were developed using the field data to predict fish and shellfish abundance (i.e., catch per unit effort [CPUE]) from key environmental variables collected concurrently with the fish sampling, namely salinity, temperature, and in some instances where it was considered an important determinant of abundance, turbidity. The newly developed statistical models were used with combinations of salinity, temperature, and turbidity (where applicable) within ranges found during the period of record in order to determine the maximum CPUE value for the model. The statistical models were then standardized to a 0 to 1 scale by the maximum CPUE value. For key environmental variables in which statistical relationships could not be developed, such as marsh habitat area and chlorophyll a, literature values and expert professional judgment were used to generate suitability indices. The final HSI equation for each species was then generated by aggregating all suitability indices – statistically and expertly derived – using the geometric or arithmetic mean.

The revised (or newly developed) fish and shellfish HSIs are an improvement over the traditional HSI approach, as it utilized independent fisheries data to develop statistically based relationships between species relative abundance and key environmental variables.

For additional information regarding the HSIs, refer to the individual species attachments:

- Attachment C3-6 : Gadwall Habitat Suitability Index Model
- Attachment C3-7 : Green-winged Teal Habitat Suitability Index Model
- Attachment C3-8 : Mottled Duck Habitat Suitability Index Model
- Attachment C3-9 : Brown Pelican Habitat Suitability Index Model
- Attachment C3-10 : Alligator Habitat Suitability Index Model
- Attachment C3-11 : Blue Crab Habitat Suitability Index Model
- Attachment C3-12 : Oyster Habitat Suitability Index Model
- Attachment C3-13 : Brown Shrimp Habitat Suitability Index Model
- Attachment C3-14 : White Shrimp Habitat Suitability Index Model
- Attachment C3-15 : Gulf Menhaden Habitat Suitability Index Model
- Attachment C3-16 : Spotted Seatrout Habitat Suitability Index Model
- Attachment C3-17 : Bay Anchovy Habitat Suitability Index Model
- Attachment C3-18 : Largemouth Bass Habitat Suitability Index Model
- Attachment C3-19 : Crayfish Habitat Suitability Index Model

7.0 Nitrogen Uptake

The potential for aquatic and estuarine ecosystems to mitigate increased loads of inorganic nitrogen (N) is perhaps nowhere more important than in the coastal region of Louisiana. Denitrification is a major pathway for the removal of inorganic nitrogen in lakes, rivers, and coastal estuaries. This reduction is biologically mediated through a series of intermediate products to gaseous nitrogen (N_2) representing a direct loss of nitrate to the atmosphere. As nitrate-enriched water masses flow through the landscape, the presence of riparian, headwater streams, and coastal wetlands can efficiently remove reactive nitrogen.

The model used in the 2012 Coastal Master Plan (Rivera-Monroy et al., 2013) was based on previous experimental studies and work performed during the Coastal Louisiana Ecosystem Assessment and Restoration (CLEAR) Program (Rivera-Monroy et al, 2003). It used the spatial statistical approach (SSA) to utilize denitrification datasets in several habitats in coastal Louisiana as well as current estimates of nitrogen loading rates for comparative analyses of different project effects. The 2017 Coastal Master Plan nitrogen uptake subroutine uses the same approach as 2012, with several updates as described below. The 2017 version is a subroutine of the ICM and uses information derived from various other subroutines to evaluate the potential fate of nitrogen (nitrate, NO_3) in different types of wetlands and open water bodies. Specifically, the nitrogen uptake subroutine uses outputs from the hydrology and vegetation subroutines.

The SSA model provides a first-rate estimation of inorganic nitrogen removal (NO_3) that can be used to assess how protection and restoration projects could affect nitrogen removal in wetlands surrounding areas influenced by management decisions. Nitrogen removal is estimated using in situ values of denitrification rates. The approach implemented in the 2017 subroutine uses classifications of vegetation type – at a cell resolution of 500 m x 500 m – and site-specific denitrification rates directly measured in coastal Louisiana. Hydrology, salinity, and temperature output from the hydrology subroutine drive output from the vegetation subroutine (i.e., spatial explicit type of wetlands including areal extension), and temperature is also used as a modifier in the calculations of denitrification. The subroutine separately estimates nitrogen removal for benthic sediments. The SSA estimates N removed in vegetated areas using information on vegetation distribution (500 m x 500 m), and adds the N removal from benthic sediment to calculate the total nitrogen (TN) removal value per coastal region. This is the final value provided by the SSA model. The total nitrogen removal obtained by the SSA represents the spatially explicit removal of nitrogen in different types of wetlands and benthic sediments, as these landscape categories change as a response to restoration actions.

For 2017, the same basic approach as that applied for the 2012 Coastal Master Plan was applied. However, as in situ values drive the rates applied in the model, an additional literature review was conducted to update the values based on the literature. The vegetation classification for which the denitrification rates are estimated was also updated to reflect the ability of the 2017 vegetation subroutine to resolve bottom land hardwood (BLH) and cypress-tupelo swamp vegetation types. For each land cover type, e.g., BLH, swamp, fresh/intermediate marsh, brackish marsh, saline marsh, and open water (with or without submerged aquatic vegetation [SAV]), a median denitrification rate was derived from the means found in the literature. This is the value applied in the subroutine, although the range of values from the available data is also reported should uncertainty analysis be conducted that can explore the sensitivity of model outputs to changes in the values.

For additional information regarding the 2017 nitrogen uptake subroutine, refer to Attachment C3-21 – Nitrogen Uptake.

8.0 ICM Conceptual Diagram and Narrative

As previously described, the dynamics incorporated in the 2012 Coastal Master Plan modeling effort combined with extensive improvements undertaken for the 2017 modeling effort resulted in an integrated process-based approach. The ICM represents many of the important processes driving coastal land and ecosystem change in the Louisiana coast. The interactions among the physical and vegetative processes included in the various subroutines are shown in Figure 13 along an idealized cross profile. The influence of changes in the physical environment and vegetation cover on water quality, habitat suitability, and fish and shellfish biomass is not currently represented in the conceptual diagram. This section is intended to provide an overview of all aspects of the ICM, including the linkages and interactions made possible through this new integrated approach to coding.

Within the ICM, temporal change is generally reflective of the temporal scale of direct measurements (e.g., 30 second frequency for hydrology, annual changes in shoreline position on barrier shorelines) and the temporal scale of the processes influencing change (e.g., growing season tolerance of vegetation to environmental conditions). Initialization conditions and forcing of the model for 50 year simulations is described in the hydrologic boundary conditions and landscape data sections below. As described in previous sections, a number of process interactions are represented only coarsely in the ICM due to lack of information or understanding, or because the ICM focuses on decadal scale coast wide change. In addition, the model development team was very aware that the purpose of the ICM is to evaluate the outcomes of an array of ecosystem restoration and protection projects both individually and in combinations. The focus was on including sufficient detail to accomplish that goal consistently across the coastal landscape.

Figure 13 shows forcing from the Gulf of Mexico in terms of tides and storms influencing water level, a Gulf salinity that is propagated into the estuary, and both tropical storm and non-storm waves that influence barrier island cross-shore and long-shore changes, respectively. Tropical storms occur throughout the 50-year ICM runs, reflecting the historical pattern of storm effects as modified by the future scenarios (Chapter 2). Sea level rise is imposed at the Gulf boundary, and the ICM propagates the effects on coastal hydrology. Many simple models of coastal wetland dynamics impose a system wide water level increase to reflect sea level rise (e.g., SLAMM; Warren Pinnacle Consulting, Inc., 2012). The ICM is not a 'bathtub' model; rather, it dynamically incorporates the effects of long-term progressive change in water level at the Gulf boundary. The ICM also has the ability to propagate elevated water levels (e.g., from tropical storms) though the hydrology compartments using a series of newly incorporated overland flow links.

On barrier shorelines, months that include tropical storm effects show a change in the cross profile caused by the event. Sand can overwash onto back barrier marshes changing elevation and potentially converting them to be dominated by swale vegetation. Depending on island shape at the time of the storm event, breaches can occur. Under non-storm conditions, Gulf waves result in long-shore movement of sediment, and island cross-shore profiles are modified monthly to show these effects. Thus, when a tropical storm impact occurs, adjustments are made based on the cross-shore profile that exists the month before the event occurs. Restoration projects change the cross-shore profile of the barrier islands/shoreline (i.e., the height, width and slope of components such as the beach, dune and back barrier marsh) and the ICM adjusts the profiles based on these profile shapes for all time periods following construction. At the end of each year, the resulting profiles are used to update the DEM and as the starting point for the following year.

At the inland margins of the ICM domain, rivers and existing flow diversions from the Mississippi River (e.g., Bonnet Carre spillway, Caernarvon, etc.) provide freshwater to the estuary (Figure 13). Freshwater is also supplied via rainfall, which is applied to all hydrology compartments consistent with the relevant future scenario. Upland streams, as well as the Mississippi and Atchafalaya Rivers also provide inputs of suspended sediment, nutrients, and other water quality parameters. Within the bays, as in the open water sections of all compartments, wind[1], waves and flow[2] re-suspend sediments from the mobile sediment pool on the bed. Four sediment components (sand, silt, clay and flocculants) are tracked. Sediments are also introduced into suspension as a result of an erosion term (calculated from historical rates) applied to wetland shorelines, including the back barrier marshes. Coast wide organic matter and bulk density values are assumed for all eroded 'edge' sediment and added as a source of total suspended sediment in the hydrology subroutine. The edge sediment load is much smaller than the other sediment sources, so this was included as a simplifying assumption. Organic matter and bulk density are varied, however, by vegetation type when converting the inorganic sediment load

[1] The diagram does not explicitly show wind re-suspending; it shows wind influencing waves, which re-suspend.

[2] The diagram does not explicitly show flow.

on the marsh surface into a vertical accretion term in the morphology subroutine. In open water, flocculation varies with salinity, which is calculated for each hydrology compartment based on direct freshwater inputs (e.g., rain, tributary streams) and inputs from adjacent compartments. Settling velocities are calculated separately for each sediment class. Stage is tracked in all compartments and in those with a wetland component, suspended sediments are moved onto the marsh when the water level exceeds the height of the marsh surface. During periods of decreasing stage, water moves back into the open water but sediment does not (i.e., it remains on the marsh). Sediment is deposited on the marsh surface based on the depth and duration of flooding and the settling velocity of the different sediment size classes. During periods of high water depth on the marsh surface, flow of water, sediment, and other constituents can occur between adjacent marsh areas through overland flow links.

Vegetation cover is adjusted on an annual basis based on the elevation of the dune/swale above the mean water level on barrier islands, and the salinity and water level conditions for the wetlands. Forested wetland species are updated on the basis of water depth, and submerged aquatic vegetation (SAV) is updated on the basis of mean summer water depth, salinity and temperature. Thirty-two different species of vegetation are tracked and adjusted based on annual hydrologic conditions and the proximity of potentially colonizing species; dune and swale species are tracked on the basis of elevation above mean water level. Individual wetland species are grouped into five habitats (fresh forested, fresh, intermediate, brackish and saline marsh) that are used to assign organic matter characteristics to the wetland soils. The resulting organic matter percentage is used in combination with the annual amount of inorganic sediment deposited on the wetland surface to determine the annual accretion on the wetland surface. This is combined with subsidence to determine annual change in wetland elevation. At the end of each year, a determination is made on whether the wetland area is maintained. For fresh wetlands, the salinity during the preceding year is used to assess whether the salinity threshold is crossed. For all other wetland types, the threshold is based on the depth of flooding. Based on these calculations for the wetlands and the end of year barrier shoreline profiles, the configuration of land and water and its elevation is assessed at the end of each year and used to update the DEM. The revised coastal DEM is used to reinitialize the hydrology calculations for the following year (e.g., new extents/depths of open water, new wetland elevations).

Water quality changes in open water areas are calculated using transport and reactions, which affect both dissolved particulate forms. Outputs include: total Kjeldahl nitrogen, water temperature, nitrate + nitrite nitrogen, ammonium nitrogen, dissolved organic nitrogen, total phosphorus, soluble phosphorus, phytoplankton as chlorophyll a, and detritus. The ICM deposits sediment onto the bed, but does not predict the fate of constituents once deposited. The water column is assumed to be fully mixed and aerobic at all locations and times. Thus, there are no transfers of nutrients from the bed to the water column of the type that can occur when the water column is anoxic, or oxygen deprived. Formulations used in the model in addition to these source/sink terms include stoichiometric relations, photosynthesis rates, temperature dependencies, phosphorus partitioning, and ammonium preference.

Various characteristics of the open water (e.g., depth, salinity, and chlorophyll a) are used in combination with characteristics of the wetland and barrier island environments to determine habitat suitability for eight species of fish and shellfish and six species of wildlife. In this manner, the suitability of the coastal system for a variety of commercially and recreationally important species is tracked on an annual basis. Some of the suitability models for species depend on habitat for others (e.g., suitability for brown pelicans depends in part on suitability for gulf menhaden). If suitability for a species depends on aspects of the coastal system that are not adjusted within the ICM (e.g., distance to human activity/communities) these values remain constant throughout the 50-year ICM simulations. In addition, ICM-generated values for daily/monthly salinity, monthly water temperature, and annual wetland distribution are provided to the EwE subroutine and are used to estimate changes in relative biomass for different life stages of 21 species of fish and shellfish (EwE is described in a later section). Habitat suitability and relative biomass calculations do not feedback to the ICM calculations. Within EwE, biomass in a year is dependent in part on biomass from the previous year. Habitat suitability for each year is calculated independently.

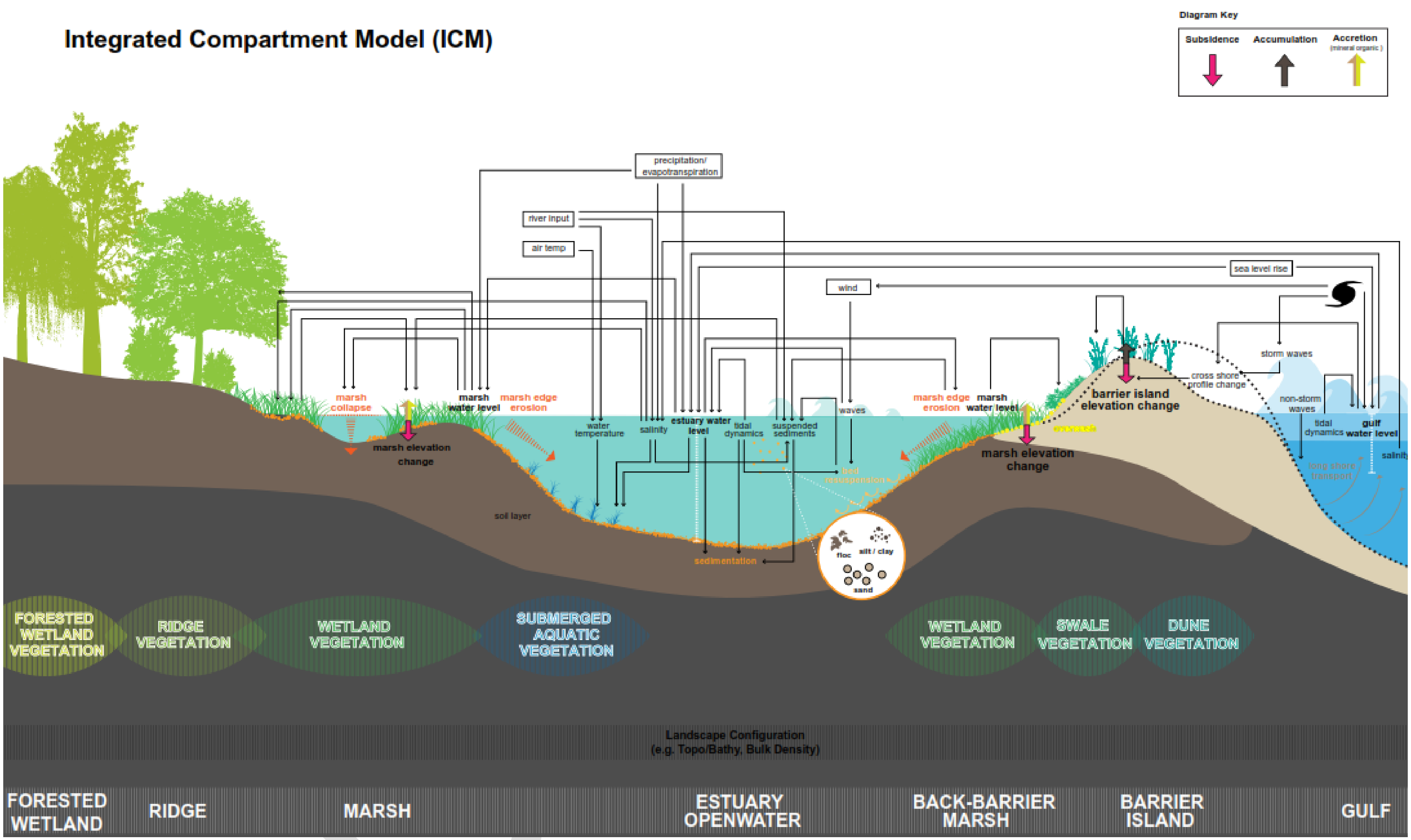

Figure 4: Conceptual overview of the processes represented in the Integrated Compartment Model (ICM).

9.0 Hydrology Boundary Conditions

Considering the effort to update the technical tools for the 2017 Coastal Master Plan, it was also critical to ensure that the most up-to-date data were used to drive calibration and validation of the newly developed ICM. As part of the task to improve input datasets and boundary conditions, a list of the data collection stations used in the 2012 Coastal Master Plan was assembled and newly available stations and sources of data to support improvements were added. The final list of data sources and stations was reviewed and approved by the broader modeling team.

Similar to the 2012 Coastal Master Plan, daily riverine inflow, hourly tidal stage, daily and discrete water quality, and daily precipitation and evapotranspiration data used to drive the ICM were collected from the following:

- U.S. Geological Survey (USGS)
- U.S. Army Corps of Engineers (USACE)
- National Oceanic and Atmospheric Administration (NOAA)
- National Oceanographic Data Center (NODC)
- Louisiana Department of Environmental Quality (LDEQ)
- Texas Commission on Environmental Quality (TCEQ)
- National Climatic Data Center (NCDC)

Missing data in the time-series were addressed using fitted relationships and linear interpolation where appropriate.

To inform the offshore stage boundary, water levels from four NOAA stations and one USGS station along the coast were used at the model offshore boundary. These stations, however, did not provide reliable datum conversions to the datum used by the ICM (i.e., North American Vertical Datum of 1988 Geiod12A [NAVD88 12A]) nor did they correct for subsidence and sea level rise. The USACE Southwest Pass gauge was used to convert to the NAVD88 Geoid12A datum and correct for subsidence and eustatic sea level rise. Additionally, further datum adjustments were made to minimize differences between the modeled stages and measured stages from CPRA's CRMS stations, which provided a consistent reference water level across the Louisiana coast near the Gulf of Mexico.

To obtain a better representation of the salinity in the offshore area, hourly salinity data from near-shore stations (as used in the 2012 Coastal Master Plan) were replaced with data from the NODC World Ocean Database (WOD). WOD is a database of Gulf measurements including salinity. These data were used to inform spatially varying, but temporally constant, salinity concentrations at the model offshore boundaries.

Wind data that was not originally used in the 2012 Coastal Master Plan were collected from the NCDC North American Regional Reanalysis (NARR) Model. The "reanalysis" incorporates observations from instruments and then assigns this output onto a regularly spaced grid of data (approximately 32 km x 32 km).

This documentation is specific to the boundary conditions used for ICM calibration and validation and the test model runs done to help identify future scenarios for use in production runs. For additional information regarding the hydrology related boundary condition data sets, refer to Attachment C3-26 – Hydrology and Water Quality Boundary Conditions. For additional information regarding how these datasets were altered to account for future scenarios in production runs, refer to Chapter 2 (Future Scenarios) and associated attachments.

10.0 Landscape Data

As described in the previous section, input data are one of the most influential determinants of model output quality. As such, an effort was undertaken to identify newly available or improved landscape specific input data to ensure the most up-to-date data were used to drive the 2017 Coastal Master Plan models.

Critical datasets for initializing the landscape components of the ICM were identified. These included: (1) a base period land and water composition dataset, (2) a base period integrated bathymetry and topography dataset, and (3) a dataset delineating the extent of vegetation community types. Each of these datasets constitutes a fundamental descriptor of the coastal landscape, and thus they affect most of the physical and biological processes that the master plan models simulate. Inaccuracies in these types of datasets manifest as inaccuracies in the models results, not only specific to the ICM, but also as it relates to the EwE fish and shellfish model and risk assessment modeling (described in later sections).

One of the most influential landscape datasets (i.e., land and water composition) is constantly changing in coastal Louisiana. Therefore, it was important to initialize models with the most up-to-date data to ensure that any land loss that has occurred since the 2012 Coastal Master Plan was accurately reflected in the base conditions of the new 2017 modeling effort. Similarly, any land gain, including the benefits from coastal restoration projects that have been completed since the last iteration of the plan, needed to be appropriately considered. For this reason, the latest available satellite imagery was compiled and analyzed to create a dataset that delineates the latest possible land and water composition of the coast.

Although land and water is a fundamental landscape descriptor, elevation is equally important when it comes to coastal modeling. The landscape composition dataset previously discussed outlines the horizontal aspect of the landscape, and the elevation data provide information on the vertical dimension. Elevation data are possibly the most critical landscape descriptor, but it is also a dataset with tremendous collection, processing, and accuracy challenges.

Finally, while the previous two datasets describe the three-dimensional landscape, the land cover classes, including the vegetation occupying that landscape, must also be described. Many coastal processes vary, depending upon the vegetation type occupying a site and as such, a dataset that describes the distribution of those classes is a necessary dataset for model initialization.

With these data priorities in mind, the 2017 Coastal Master Plan team undertook a rigorous effort to create datasets, which represent the best available data describing the landscape in coastal Louisiana. The data were collected from a multitude of sources, including satellite imagery and field data. While data collection dates vary, particularly with regard to elevation data, the datasets are intended to represent the late 2014 (November) time period. This served as the initialization time period for the 2017 Coastal Master Plan modeling effort. For additional information regarding the landscape datasets used in the ICM, refer to Attachment C3-27 – Landscape Data.

11.0 Tropical Storms in the ICM Boundary Conditions

Another improvement for the 2017 Coastal Master Plan modeling is the ability to capture effects of tropical storms (i.e., hurricanes and tropical storms) on the geomorphic evolution of the landscape. The ICM is driven with long-term records that include tropical storm-associated winds, precipitation, water levels, and waves. While a basic historic record of tropical storm occurrence is available for the Louisiana coast, the archive of historic data is not adequate to provide the level of detail required as input to the ICM. This section describes the approach used to identify approximations of tropical storms derived during a Federal Emergency Management Agency (FEMA) study of the Louisiana coast for use in the ICM boundary conditions. As part of the FEMA analysis, a suite of synthetic tropical storms was developed by USACE to represent probabilistic storm impacts along the Louisiana coast (USACE, 2008). The FEMA "storm suite" does not include very low-intensity events (i.e., central pressure > 975 mb), but the suite of synthetic storms does cover the range of hurricane-strength historical storms. Using the FEMA storm suite to approximate the historical 50-year tropical storm record compensates for sparse historical data and supplies consistent boundary conditions throughout the ICM domain for use in the landscape modeling.

As part of the 2012 Coastal Master Plan landscape modeling, the effects of tropical storms were included in only a few aspects of landscape dynamics. For instance, sediment deposition by storms in coastal marshes was assumed to occur at a constant annual average rate. Other effects, such as barrier island erosion and overwash could not be reflected in the analysis due to limitations in the modeling approach. Although these coastal dynamics are included in the 2017 Coastal Master Plan modeling, data for wind conditions, surge levels, and wave heights are available only at sparse gauge locations that do not coincide with the locations where data were needed for the ICM boundaries. Therefore, tropical storm boundary conditions for the ICM were derived from an existing set of synthetic hurricanes (developed for the abovementioned FEMA storm suite), for which detailed wind, surge, and wave model outputs were readily available at the spatial and temporal resolution required.

The HURricane DATabases 2 (HURDAT2) dataset was used to characterize historical storms that made landfall along the central, northern Gulf coast and generated significant surge and waves along coastal Louisiana. Each historical hurricane in the 50-year record (1963-2012) along the Louisiana coast was aligned with an individual storm in the synthetic storm suite, according to the approximate comparison of meteorological storm parameters. The alignment of storm events from the FEMA synthetic storm suite was completed by comparing storm track, central pressure, forward speed, and maximum wind speed. The composite of all identified synthetic events constitute an approximation of the historic hurricane record. While synthetic storm events do not exactly match all the details of their historical counterpart, the ICM is used to predict long-term trends for which the ensemble effects of all the storm events are more important than the accuracy of any discrete event in particular. Several options were developed to represent the historical pattern using the synthetic storms. Potential changes to the historical synthetic storm suite to represent changes in tropical storm intensity and frequency due to climate are addressed as part of 2017 Coastal Master Plan future scenarios (Chapter 2 and associated Attachments).

Tropical storm-induced precipitation data were also required by the ICM. Precipitation intensity and volumes for each representative synthetic storm event were calculated using the same empirical relationship used in the CLARA model as part of the 2012 Coastal Master Plan (Johnson et al, 2013).

The 2017 hydrology subroutine explicitly captures the effects of these events by applying elevated water levels (i.e., storm surge) at the offshore boundary and the storm's wind field temporally and spatially along the storm's path. For each event, sediment is delivered from the offshore compartments to the marsh as sediment is resuspended from the bed in open water due to higher wave energy, and the marsh is inundated due to higher water levels.

For additional information regarding the development of the 50-year historic tropical storm record, refer to Attachment C3-3 – Storms in the ICM Boundary Conditions.

12.0 ICM Calibration and Validation

As described in previous sections of this chapter, a number of technical advancements have been made for the models being used to inform the 2017 Coastal Master Plan. With continued advancements also comes the need to ensure thorough calibration and validation. This section provides an overview of the calibration and validation effort undertaken for the ICM subroutines.

Typically, key model parameters are identified by model developers and become the focus of calibration and validation efforts. Field or laboratory measurements are needed to serve as a "reference" against which model output is compared. The key model parameters are then fine-tuned until the model output compares well to the field/laboratory observations. Through the calibration process, a base or optimum value is established for each parameter of interest. Once this base value is established, no further changes to the key model parameters are allowed. At this point, and using these base values, additional model simulations are performed using an independent dataset that was not used in the calibration. This is called model validation. Both graphical and statistical metrics can be used to assess the model performance and how well it replicates the natural system being modeled. The understanding gained and the statistical evaluation of the level of agreement between the model output and field measurements is referred to as model performance assessment.

The ICM subroutines included in the calibration and validation effort are listed below, and the datasets and approaches used are provided in Table 3**Error! Reference source not found.**:

- Hydrodynamics
- Water quality
- Vegetation
- Morphology
- BIMODE (barrier islands)
- Habitat suitability indices (HSIs)

Unless otherwise noted in Table 13, the available record of field measurements that was deemed to be of acceptable quality and level of completeness and suitable to calibrate and validate the ICM was from 2006 – 2014. The period 2010 – 2014 was reserved for calibration while 2006 – 2009 was reserved for validation.

The modeling team reviewed model outputs and made adjustments to the model as needed until each model output was successfully calibrated (based on the approach/metrics in Table 13. For some model outputs, setting a quantitative metric was not possible; therefore, best professional judgment of a subject matter expert familiar with both the natural system and the model was the best approach to determine when the model had reached its optimal predictive ability.

For additional information regarding the calibration and validation effort for the ICM, including methods, analysis, and summary statistics, refer to Attachment C3-23 – ICM Calibration and Validation. EwE calibration is documented in Attachment C3-20 – Ecopath with Ecosim (EwE).

Table 3: Overview of the ICM Calibration and Validation Effort.

Model Output	Data Used	Available Record	Approach/Metrics	Model Parameters to Adjust During Calibration
Stage	LDEQ, CRMS, USGS, NOAA	2006-2014	RMSE of 10-20%	• Cell/link dimensions • Observed tidal datum corrections • Hydraulic equations
Salinity	LDEQ, CRMS, USGS	2006-2014	RMSE of 20-30%	• Diffusivity
Flow	USGS	2006-2014	RMSE of 20-30%	• Cell/link dimensions • Observed tidal datum corrections • Hydraulic equations
Suspended Sediment	Long-term averages of grab TSS samples from USGS and LDEQ & reflectance imagery	varied	Best professional judgment based on long-term average TSS & spatial patterns identified from reflectivity imagery	• Resuspension coefficients
Sediment Accumulation	CRMS soil properties & measured accretion rates	varied	Best professional judgment based on marsh accumulation and mean suspended sediment concentration	• Resuspension coefficients • Marsh exchange flow
Nitrogen	LDEQ	2006-2014	Best professional judgment based on WQ grab sample datasets	• Sediment denitrification rate • Minimum nitrification rate
Algae	LDEQ	2006-2014	Best professional judgment based on WQ grab sample datasets	• Sediment denitrification rate • Salinity at which algal growth is halved • Phytoplankton mortality rate

Phosphorus	LDEQ	2006-2014	Best professional judgment based on WQ grab sample datasets	• Detritus dissolution rate • Phytoplankton respiration rate
Long-term (25-yr) accretion	Cesium cores (>100 cores)	2011-14 calib; 2006-10 valid	RMSE of 20% for mean annual accretion by region (PB, AA, CP) by wetland type	• Bulk density • Organic matter
Multi-year land area change rates	Historic land change rates from satellite imagery (Landsat)	2011-14 calib; 2006-10 valid	Within 10% of measured land change rates by ecoregion by wetland type	• Marsh collapse threshold • Only if needed: o Storm sediment distribution o Background land change rate o 2-zone sediment deposition
% cover per modeled vegetation species	CRMS vegetation data	2006-2014	Best professional judgment based on capturing stability or trajectories of change at 392 CRMS stations for all species	• Mortality and establishment tables for species for which the distributions are over or under estimated
Barrier island long-shore transport	BICM, LiDAR, historic reports	2003-2012	Best professional judgment based on accepted long-shore transport rates	• Long-shore transport coefficients (to obtain net long-shore transport rates that match sediment budgets presented in historic reports)
Barrier island cross- shore transport	BICM	2010	Best professional judgment based on overwash extent as calibrated for previous SBEACH efforts	• SBEACH transport rate coefficient • Slope dependent coefficient • Transport rate decay coefficient • Overwash
HSIs	n/a	n/a	Expert validation by reviewing outputs, associated input data, and determining if spatial pattern and magnitude was reasonable	

13.0 Ecopath with Ecosim (EwE)

A fish and shellfish community modeling approach was used in the 2017 Coastal Master Plan to evaluate effects of individual restoration and protection projects and alternatives (groups of projects) on fish and shellfish communities (hereafter referred to as fish) over fifty years under multiple environmental scenarios (i.e., multiple values of sea level rise, subsidence, etc.). To this purpose, a spatially explicit ecosystem model was developed in the Ecopath with Ecosim (EwE) software suite. The Fish and Shellfish Community Model simulates fish biomass distribution through time and space. This section describes the modeling approach, key assumptions of the model and modeling approach, and improvements made to fit the needs of the overall 2017 Coastal Master Plan modeling effort. The resulting Fish and Shellfish Community Model is described and examples of response curves and output are provided in this section. The methods planned to calibrate and validate the model, to provide a measure of model uncertainty, and to link the Ecospace model to the ICM are also provided.

13.1 Modeling Approach

A fish and shellfish community model that describes an extensive food web, represents predator-prey interactions, includes responses of fishes to environmental factors, and has the option of movement for nektonic species has the ability to simulate fish biomass and distribution in response to restoration and protection projects. In addition, it has become exceedingly clear that fishing is a very important determinant of fish and shellfish biomass in any ecosystem where fishing occurs (Worm et al., 2009) whether a species is targeted or a portion of the bycatch. Louisiana, known as the Sportsman's Paradise (Katner et al., 2001), and the state with the second highest commercial landings (by weight) in the United States (NOAA, 2014), is not an ecosystem where the effects of fishing can be disregarded. Ecopath with Ecosim (EwE) is a community modeling approach that can be used to simulate the combined effects of all of these ecosystem processes.

EwE is an open source ecosystem modeling software, originally developed by Polovina (1984) to model trophic interactions and to estimate mean annual biomass in a coral reef ecosystem. Since that time, the model has been greatly improved and is used to model ecosystems worldwide (Christensen and Pauly, 1992; Walters et al., 1997; Walters et al., 1999; Walters et al., 2000). The EwE modeling framework now consists of three modules: Ecopath, Ecosim, and Ecospace. The spatial application, Ecospace, was added in 1999 (Walters et al. 2000) and was included in a major recoding effort in 2006 to make the modeling suite more user-friendly, easier to adjust to individual modeling needs, and easier to link to other models. The EwE source code was migrated to the .NET programming environment, and this transition is one of the primary factors allowing for the development of a new and flexible spatial-temporal data framework in Ecospace.

All three modules have been used to develop the Fish and Shellfish Community Model. In short, Ecopath is a virtual representation of the food web of an ecosystem, including flows and pools of biomass within this food web. Ecosim then allows for temporal simulations of changes in biomass of groups in the model (which could be species or functional groups) in response to changes in water quality variables (such as nutrient loads and salinity) and fishing over time. Because of the trophic interactions represented in the initial food web, both direct and indirect effects of these drivers and forcing functions are made evident. Lastly, Ecospace allows for spatial and temporal simulations of biomass change of each of the groups in response to spatially and temporally explicit drivers, forcing functions, and habitat characteristics. This feature not only provides information on the spatial distribution of each group in the model, it also improves estimates of total biomass changes of each group over the course of the model run because movement of consumers, and spatially explicit habitat characteristics of the system are taken into consideration.

13.1.1 Ecopath

Ecopath is a mass-balanced ‘snapshot’ of the ecosystem. Species or groups in Ecopath can be divided into multiple life stages. This approach is referred to as the multistanza approach and can include a juvenile and adult for each group, or multiple life stages per group when ontogenetic shifts occur at several instances in the life cycle. The model is mass-balanced over a set time period; for the Fish and Shellfish Community Model this period is 1 year, which is most commonly used in EwE models (Christensen et al. 2008). The assumption of mass-balance implies that the flow of biomass into the model must equal the flow of biomass out of the model over the period of a year. Mass-balance occurs within the model when two governing equations are satisfied. The first equation describes the production term and can be expressed as:

$$B_i \cdot (P/B)_i \cdot EE_i - \sum_{i=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} - Y_i - E_i - BA_i = 0 \qquad (1)$$

Where: B_i and B_j are the biomasses of the prey (i) and predators (j) respectively; $(P/B)i$ the production/biomass ratio; EEi the ecotrophic efficiency, which is the proportion of the production that is utilized in the system; $(Q/B)j$ the consumption/biomass ratio; $DCji$ the fraction of prey (i) in the diet of predator (j); Y_i the total fishery catch rate of (i); Ei the net migration rate (emigration-immigration); and BA_i the biomass accumulation rate for (i). The second master equation ensures energy balance within each group as follows:

Consumption = production + respiration + unassimilated food (2)

To develop the Ecopath model, a proportional diet and at least three of the following parameters: initial biomass, production/biomass ratio, consumption/biomass ratio, and ecotrophic efficiency must be provided for each species or group. Using the master equations, the model will solve for the parameters that were not provided. After iterative tuning and calibration, a mass-balanced Ecopath model can be achieved. The resulting balanced model provides output that can be used to investigate food web dynamics, ecosystem networks, keystoneness, mean trophic level indices, among many others. It also provides a base model to use in temporal dynamic simulations in Ecosim, or temporal and spatial dynamic simulations in Ecospace.

13.1.2 Ecosim

Applying the initial parameters derived from the first master equation in Ecopath, the Ecosim module of EwE can be invoked. Ecosim re-expresses the system of linear equations from Ecopath as a system of coupled differential equations to predict future outcomes. Environmental factors can influence trophic interactions when included as forcing functions, which are used to alter the effective search rate of predators in a way determined by species-specific response curves. The effective search rate in Ecosim allows predators to spend more (or less) time foraging in arenas where prey are concentrated. To include forcing functions in the model, a dataset with monthly values of the environmental variables of interest is uploaded to the model. In addition, response curves are created that represent the tolerance ranges of each group in the model for the specific environmental variable.

13.1.3 Ecospace

Ecospace is the spatially explicit and time dynamic module of the EwE software package. In this module, the same set of differential equations applied in Ecosim is now applied in every grid cell over a geo-referenced base map (Christensen et al., 2004; Walters et al., 1997). Consumption rates are based on the Foraging Arena Theory (Walters and Martell, 2004), as is the case in Ecosim, allowing Ecospace to represent biomass and consumption dynamics over two-dimensional space (Christensen et al., 2008; Walters et al., 1999). While Ecosim runs in each Ecospace grid cell, a portion of the biomass of each group will move to adjacent grid cells in search of better living conditions with movement rate m in km yr^{-1}. Movement rate (m) can be user defined, and is set at a default of 300 km yr^{-1} when no specific swim speed is known for a specific group.

Groups in Ecospace respond to environmental drivers and habitat features following the Habitat Capacity Model (Christensen et al., 2014). External data or model output of environmental variables (salinity, temperature etc.), coupled to response curves that describe how groups respond to these drivers, are used to compute the suitability or Habitat Capacity (C) in a grid cell per time step. C is a unitless value between 0 (unsuitable) and 1 (maximum suitability); low C reduces consumption by reducing the size of the foraging arena area in a grid cell. In addition, movement is affected such that movement (of a specific group) towards unsuitable habitat in a neighboring cell is slowed as a function of C.

Fishing fleets (which can represent recreational fishing as well) are included and dynamic in Ecospace. Ecospace takes the Ecosim time series of fishing effort and distributes the effort across the map based on the biomass in a cell. Fishing mortality rates (F) are initially distributed between fleets based on the distribution in the underlying Ecopath base model. During an Ecospace run, F's are distributed over cells using a gravity model; the proportion of effort allocated to any particular cell is assumed proportional to the sum over groups of the product of the biomass of the target species and profitability of fishing in that particular cell (Christensen et al. 2008). Profitability is not calculated in the Fish and Shellfish Community Model and is directly related to biomass (making the gravity model solely respond to the biomass of target groups in a cell).

13.2 Improvements to the 2017 Coastal Master Plan

Several specific improvements to the EwE software and approach were made to accommodate the needs of the 2017 Coastal Master Plan. These can be summarized as follows:

- **Monthly time series** - Up to the most recent release of the EwE software, the 'fitting to time series' procedure used during calibration could only be achieved at an annual resolution. The software has now been modified to incorporate either monthly or annual biomass time series data.
- **Geospatial projection of model area** - The Ecospace module of the EwE software applies the ecological dynamics of a marine food web across a grid of cells. Traditionally, this grid is geo-referenced to decimal degrees longitude [-180, 180] and latitude [-90, 90], where cells taper at higher latitude ranges – the common WGS84 or EPSG:4326

projection. Ecospace automatically takes this projection into account in its functional groups dispersal calculations. For the 2017 Coastal Master Plan Fish and Shellfish Community Model, these calculations needed to be modified to enable habitat feature data input to Ecospace to be mapped to a local UTM spatial projection with highest positional accuracy.

- **Excluding map cells** - Historically, users could only exclude Ecospace map cells from computations by turning these cells to land. This would yield confusing maps with unrecognizable land contours. In response, the concept of excluded cells was introduced to the Ecospace model. These excluded cells do not contain ecosystem dynamics, are not considered in the Ecospace computations, and are not rendered in the map displays. In addition, a feature is added to explicitly display which cells were excluded on output maps.
- **Sharing external spatial datasets between computers** - The Ecospace module of the EwE software recently gained capabilities to be driven by external spatial-temporal datasets, a feature that is extensively used for the 2017 Coastal Master Plan Fish and Shellfish Community Model. These external data sets cannot be embedded within an EwE model because they tend to be model-derived datasets that frequently update and are of prohibitive file size. The process of connecting to these data is detailed in Steenbeek et al. (2013). Since the 2017 Coastal Master Plan Fish and Shellfish Community Modeling exercise would be executed by scientists of different institutes in different locations, this system needed to be extended to offer support for shared use of the same model with accompanying external spatial data via cloud-based transfer media.
- **Adding new ways to shape response curves** - The Ecosim and Ecospace modules contain forcing functions and mediation functions through which temporal and spatial dynamics of the model can be influenced. The predefined mathematical distributions already available in EwE did not contain shoulder and trapezoid distributions that would be needed for the 2017 Coastal Master Plan Fish and Shellfish Community Model. The EwE software now offers ten different distributions in addition to the ability to sketch in curves. The trapezoid distribution is extensively used in the Ecospace model developed to support the 2017 Coastal Master Plan.

13.3 Fish and Shellfish Community Model Description

The Fish and Shellfish Community Model represents 55 groups, 41 of which represent a life stage of a species and fourteen represent species aggregates (e.g., zooplankton; Table 14). The model was (initially) calibrated in Ecosim with 10 years of environmental parameter output derived from models supporting the 2012 Coastal Master Plan and biological field data collected during 2000-2009. The spatial grid for the Fish and Shellfish Community Model I was developed with a 1 km x 1 km resolution that represents coastal Louisiana (Figure 14). Environmental drivers in the model are salinity, temperature, Total Kjeldahl Nitrogen, total suspended solids, percent wetland, percent upland, depth, and percent cultch. Species respond to monthly values of each of these drivers with species-specific response curves (Figure 15). Suboptimal conditions for a specific species reduce its foraging arena area in an Ecospace grid cell following the Habitat Capacity Model (Christensen et al. 2014).

Table 4: Listing of all groups in the Fish and Shellfish Community Model.

Group name	Group name	Group name
juvenile Atlantic croaker	juvenile gulf sturgeon	Juvenile sheepshead
adult Atlantic croaker	adult gulf sturgeon	adult sheepshead
juvenile bay anchovy	killifishes	silversides
adult bay anchovy	juvenile largemouth bass	juvenile southern flounder
benthic algae	adult largemouth bass	adult flounder
benthic crustaceans	mollusks	juvenile spot
juvenile black drum	oyster drill	adult spot
adult black drum	oyster (spat)	juvenile spotted seatrout
juvenile blue catfish	oyster (seed)	adult spotted seatrout
adult blue catfish	oyster (sack)	juvenile striped mullet
juvenile blue crab	phytoplankton	adult striped mullet
adult blue crab	juvenile red drum	juvenile sunfishes
juvenile brown shrimp	adult red drum	adult sunfishes
adult brown shrimp	SAV	juvenile white shrimp
detritus	sea birds	adult white shrimp
dolphins	juvenile sea catfish	zoobenthos
grass shrimp	adult sea catfish	zooplankton
juvenile menhaden	juvenile sharks	
adult gulf menhaden	adult sharks	

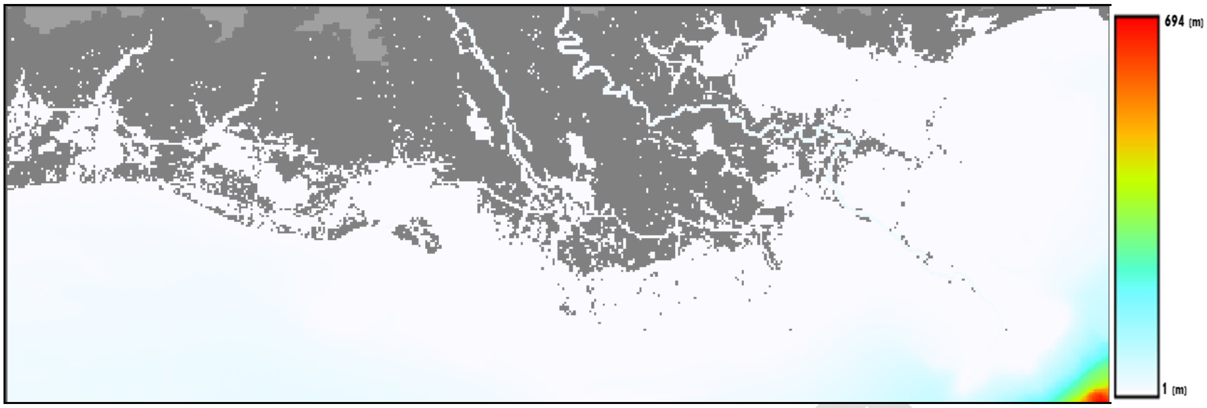

Figure 5: Model area of the coast wide Fish and Shellfish Community Model. While grey cell are inactive fish have access to all other areas, which include open water as well as wetlands, depending on their habitat preferences. Warmer colors in the active cells indicate increasing depth.

Since EwE has a monthly timestep, the model may miss short-term (< 1 month) unsuitable conditions that could have an effect on long-term biomass. As it was determined that this could pose an issue for oyster biomass estimates, Oyster Environmental Capacity Layers (OECLs) that can be read into Ecospace were developed. OECLs determine habitat capacity per month based on daily values of salinity, temperature, and TSS. The OECLs are then read into Ecospace in the same manner as the other environmental drivers.

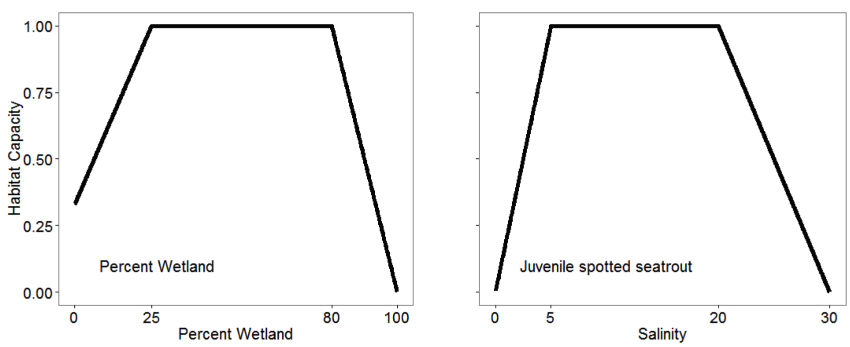

Figure 6: Examples of response curves. The first curve is applied to several species (mostly at the juvenile life stage) that are associated with wetlands. The second curve is one of the species-specific response curves to salinity and represents the response of juvenile spotted seatrout to salinity.

The output of an initial Ecospace model built for three basins in coastal Louisiana (i.e., Barataria Bay, Breton Sound, and Lake Pontchartrain) reflects fish biomass and fishery landings trends seen during the 2000-2009 time period. Twenty and 50-year simulations (2009-2059) have demonstrated that the Ecospace model remains stable while running over such long time periods. Preliminary example results of a group low in the food web (phytoplankton) and a group high in the food web (adult red drum) are shown in Figure 16 and Figure 17. These results highlight the ability of the model to provide output on decadal time scales, to incorporate fish response to environmental parameters, and to reproduce observed biomass.

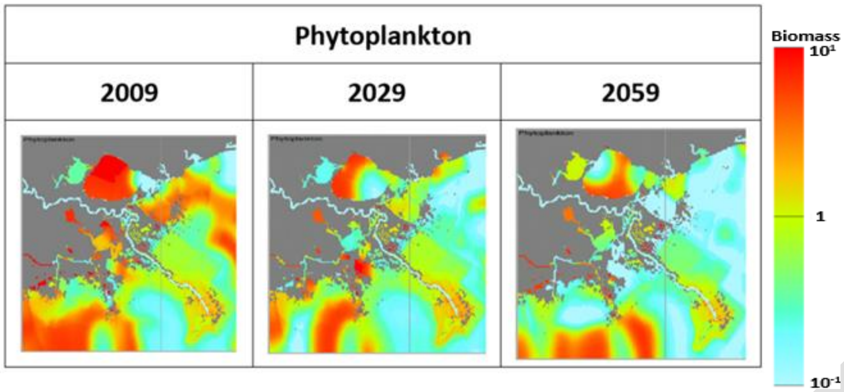

Figure 7: Ecospace model output for phytoplankton. The scale bar in the legend represents relative biomass on a log scale compared to initial biomass of this group.

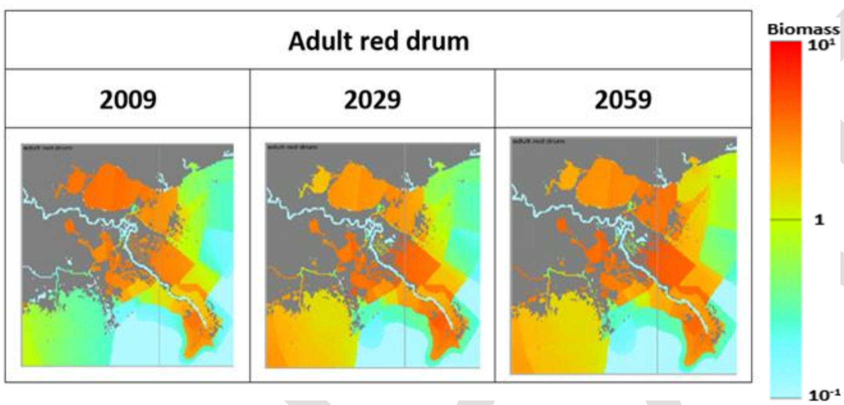

Figure 8: Ecospace model output for adult red drum. The scale bar in the legend represents relative biomass on a log scale compared to initial biomass of this group.

13.3.1 Key Model Assumptions

- The model mass balances over a period of a year.
- The species included in the model together provide a good representation of the food web in Louisiana estuaries.
- The diet of each group consists of species/groups present in the model, and diet switching does not occur.
- Including changes in environmental parameters at a monthly time step will realistically reflect effects of a changing environment on fish (except oyster; see next bullet-point).
- Including changes in salinity, temperature and TSS at a daily time step will realistically reflect effects of changes in environmental parameters on oysters.
- Movement of fish in the Ecospace model is only affected by the suitability of the environment determined by environmental parameters, habitat features, and levels of predation and fishing. Seasonal migration patterns are therefore not reflected in the model, as these movements do not stem from movement away from unsuitable conditions.

- Fleets included are representative of fishing in Louisiana.
- Fishing effort remains constant over the simulation time.
-

13.3.2 Model Tuning and Testing

Model calibration in EwE was carried out in the Ecosim module. During model calibration, biomass and landings output of groups in the model are fitted to observed biomass data and landings data for each group for which data are available. Model fitting in Ecosim is accomplished by having the model estimate the 'vulnerability of a group to predation' (v_{ij}) term that produces a better fit to the observed data. During the Fit to Time Series procedure, the model is iteratively fit to observed values with a new set of v_{ij}, and the sum of squared deviations (SS) of the observed logarithmic (log) biomass values is used to determine if these changes in allow the model to better recreate historical patterns of biomass (Christensen et al., 2008). The SS calculation used within Ecosim during the fitting process where Ecosim tests all combinations of v_{ij} values is as follows:

$$SS = \sum_i^{nts}\left(\sum_t^{nobs_i} w_i \log(o_{it}/p_{it})^2\right) \tag{3}$$

Where: nts is the number of time series loaded; $nobs_i$ the number of observations in time series i,;w_i is the weight of the time series i; o_{it} is the observed value in time series i at time step t and p_{it} is the Ecosim predicted value for variable i at time step t.

The procedure stops fitting the model with new values to the observed data when no lower SS value is found by adjusting v_{ij}. These values acquired in Ecosim are then transferred to Ecospace. To provide goodness of fit measures that are comparable to other models, the root mean square error (RMSE) is used to assess the fit of predicted to observed as well. Further fine-tuning occurs by running the model in Ecospace, checking biomass and biomass distributions of each run, and changing input parameters manually within the range of reported values to produce realistic biomass and biomass distributions.

A sensitivity analysis was conducted in Ecosim using Monte Carlo simulations. This feature was used to vary the initial biomass of all groups in the model with a coefficient of variation (CV) of 0.1 over 20 model runs. The small CV was chosen to reveal whether small changes in initial biomass result in large changes in output biomass. This tests the robustness of the model, and also gives insight as to what the effects could be of changing certain parameters during the fine-tuning process. By having the biomass of all species vary at the same time, the potential impact of the changed biomasses of other species in the model through trophic interactions are tested with these Monte Carlo trials as well.

To spatially validate the model, the coast was first subdivided into ecoregions. Subsequently, per-region model output is compared to field collections from the corresponding ecoregion, and goodness-of-fit (i.e., RMSE) calculated. This method tests the quality of biomass predictions and spatial distribution. Using information on goodness of fit of the model to field collections calculated during model validation, confidence intervals can be created per ecoregion, per species that serve as an indication of model uncertainty.

13.4 Linking ICM to EwE

The 2017 Coastal Master Plan modeling effort aims to simulate a large number of projects under multiple environmental scenarios. The Fish and Shellfish Community model uses output of salinity, temperature, Total Kjeldahl Nitrogen, total suspended solids, and any changes in wetland coverage and habitat features from the ICM to drive changes in fish biomass and distribution. Due to the number of model runs needed for the 2017 effort (e.g., hundreds), it was necessary to automate data transfer from the ICM to the Fish and Shellfish Community model. The process by which model linking occurs between EwE and the ICM is described below.

13.4.1 Habitat Capacity Model

The Habitat Capacity Model offers the ability to drive foraging capacity for a species based on the cumulative impacts of physical and/or environmental factors such as depth, salinity and temperature. The Ecospace Spatial Temporal Framework is capable of loading Geographic Information System (GIS) files that are used as spatial-temporal forcing data to drive changes over space and time to the inputs of the Habitat Capacity Model.

13.4.2 EwE Console App

To facilitate the linking of EwE to the ICM, a console version of EwE was developed that allows EwE to be configured and run from a text command line file. This version of EwE contains all the core computational functionality without the Scientific Interface. This allows multiple instances of EwE to be run at the same time from different inputs, with outputs from each instance of EwE being sent to different output directories. The command line file contains all the required configuration information for the Ecospace Spatial Temporal framework to load physical or environmental GIS input files that are used to drive changes in the Habitat Capacity Model.

13.4.3 ICM

The ICM joins models into a chain using the outputs from one model as the input to another. The console version of EwE is added to this chain by formatting the outputs from various models in the ICM into GIS input files that are read in via the Ecospace Spatial Temporal Framework. Once the file format conversion is done a new EwE text command line file is written and EwE is run on the new input data.

For additional information on the EwE model used for the 2017 Coastal Master Plan, refer to Attachment C3-20 – Ecopath with Ecosim (EwE).

14.0 Storm Surge and Wave Model Overview

The goal of the storm surge and waves model used in the 2017 Coastal Master Plan is to evaluate various coastal restoration and protection projects and the associated benefits with regards to storm surge and wave height reduction. Storm surge and wave climate responses for initial conditions and each future condition and project action were simulated using the coupled ADvanced CIRCulation (ADCIRC) and unstructured Simulating WAves Nearshore (UnSWAN) model system. Both models use an unstructured mesh, which allows for variation of model resolution from coarse in the open ocean to very fine near islands, channels, levees, and other areas where flow and wave radiation stress gradients are large. The unstructured mesh developed for the master plan allows for a precise representation of the topographic and bathymetric features and accurate representation of the flow conditions.

14.1 Comparisons between 2012 and 2017

In order to save on computational costs for the 2012 Coastal Master Plan, the inland extents of the master plan storm surge and waves model were defined by the extents of output locations required for the risk assessment model (Johnson et al., 2013). Beyond the output locations, external weir boundaries were applied in order to minimize computational overhead associated with areas not flooded by storm surge. To additionally reduce the computational overhead, interior reaches of polders were removed from the model as well. For instance, the New Orleans polder areas, which are surrounded by levee protection systems on all sides, are not included in the model simulation. Flood depths in polder areas are accounted for directly by the risk assessment model via the estimation of overtopping volumes using the storm surge and waves model output on the unprotected side of the polder (Johnson et al., 2013).

As part of the 2017 Coastal Master Plan, the 2012 models were updated to improve the representation of storm surge across Louisiana while maintaining the mission of providing a high-speed, physics-based modeling approach. The model geometry was updated in three critical ways: expansion of the inland extents, additional model resolution in select areas to enhance model skill, and inclusion of protected areas like the New Orleans polder areas. Polders were added to the storm surge and waves model to improve accuracy on the unprotected side and for quality review purposes. Figure 18 shows the changes in the model domain between 2012 and 2017 model versions with updated protected areas highlighted.

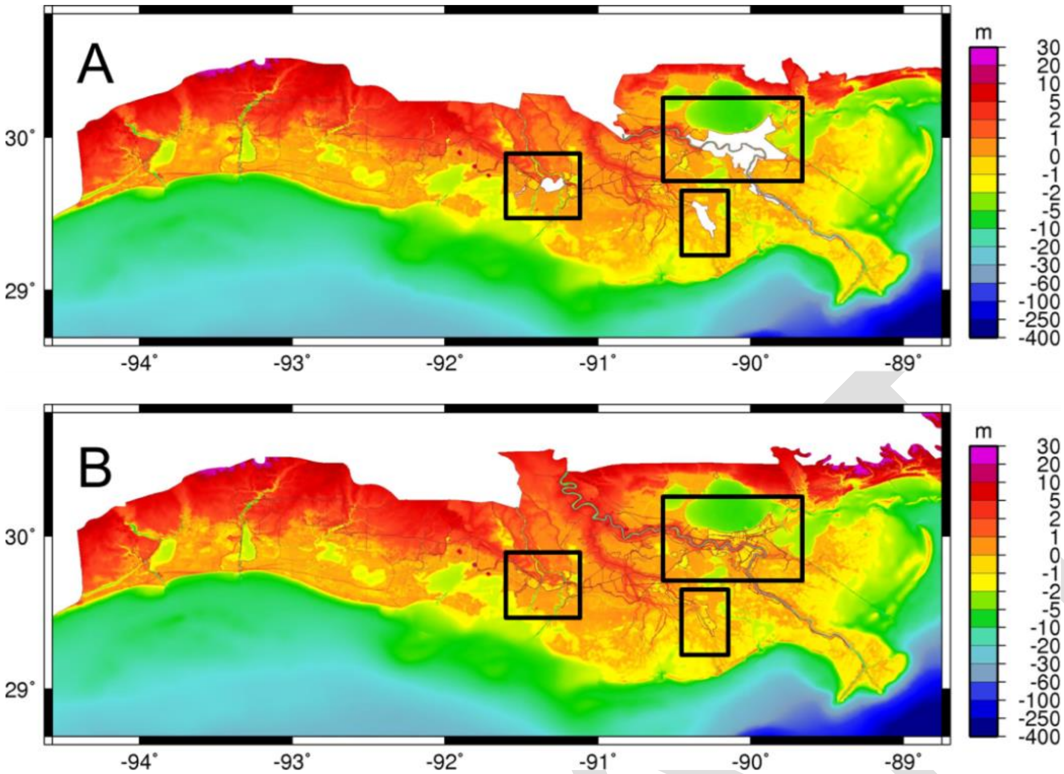

Figure 9: The (A) 2012 and (B) 2017 model elevations and updated polders. Warmer colors indicate higher elevations. Black boxes identify areas of model improvement within polders for the 2017 analysis improvements.

The critical ADCIRC and UnSWAN model inputs are elevation data at each node, surface roughness characteristics (e.g., bed roughness friction and land surface directional effective roughness length), initial and boundary conditions and system driving forces (inflows at the Mississippi and Atchafalaya Rivers, hurricane wind fields, hurricane pressure fields and tides at the open ocean boundaries).

Bathymetry and topography influences propagation and attenuation of wind-waves and surges. In the 2012 Coastal Master Plan, topography and bathymetry data applied to the model were the digital elevation model (DEM) output from the wetland and barrier shoreline morphology models (Couvillion et al., 2013; Hughes et al., 2012) for initial and future conditions. Accurate mapping of the elevation at each computational node is essential to correctly simulate inland flood propagation. Unique treatment of bathymetry, topography and pronounced vertical features (e.g., levees and highways) is critical to accurate elevation mapping. The 30-meter resolution DEM output was interpolated onto nodes applying a mesh scale averaging technique, which applies the area-weighted average according to the adjacent elemental resolution. For the development of the initial conditions mesh in the 2012 analysis, bathymetry and pronounced vertical features were mapped onto the mesh directly from previous ADCIRC model meshes developed in Louisiana by leading experts (USACE, 2008a-c) and updated based upon additional site specific survey data. For future conditions, elevations for all areas in the model, including bathymetry and pronounced vertical features, were updated based on outputs from the wetland and barrier shoreline morphology model to account for land subsidence and accretion. Additionally, future conditions design elevations for features such as levees were accounted for where necessary. Since the 2012 analysis, the 2017 initial conditions model elevations have been updated where new topography and bathymetry data were available. The same interpolation schemes and application methodologies were applied as the 2012 analysis. Model elevations for future conditions in the 2017 analysis will be provided by the ICM.

Surface roughness characteristics are critical nodal attributes as they are required for estimates of the wind energy input at the air-sea interface and energy dissipation at the seabed. In the case of water flowing or waves propagating over a surface, the bottom friction force is quantified using the Manning's *n* coefficient and the widely-used Manning's hydraulic equation. ADCIRC is able to convert Manning's *n* to a roughness length for the UnSWAN model's Madsen friction formulation. In the case of air flowing over land or water, directionally varying roughness lengths (Z_0) determined by the FEMA hazard loss estimation methodology program are used to adjust the wind boundary layer (FEMA, 2005). Both the Manning's *n* and Z_0 are relatively small coefficient values and generally constant over the water regions, with the exception of upwind effects associated with Z_0. Variations exist in the overland region, where land cover conditions vary from urbanization to agriculture, forests, swamps and marshes, as categorized in the Land Use and Land Cover (LULC) dataset by the U.S. Geological Survey. For the 2012 analysis, the LULC data were used outside of wetland areas to assign the surface roughness, while wetland morphology model land/water data (Couvillion et al., 2013) and vegetation model data (Visser et al., 2013) were applied in coastal wetland and open water areas. The mesh scale average technique applied for elevation mapping was employed to characterize the surface roughness characteristics at each node. The designation of Manning's *n* and Z_0 values for each class of land cover was guided by previous studies (Arcement and Schneider, 1989; Dietrich et al., 2011; USACE, 2008a-c). The 2017 model application will use the same surface characteristics. Though the characteristics will be updated for future conditions analyses based on ICM outputs rather than outputs from individual wetland morphology and vegetation models. Additionally, if updated LULC data are available, the initial conditions mapping will be revised.

The model initial conditions include a mean sea level adjustment, which is attributed to datum conversion, seasonal sea level fluctuation, and eustatic sea level rise for future conditions. Model boundary conditions include riverine inflows for the Atchafalaya and Mississippi Rivers and internal/external flow boundary conditions such as weir boundaries for levee systems. Tides are included in the model simulations of historic events for model validation; however, tides were not included in the simulation of synthetic storms and are instead accounted for as part of the risk assessment model inundation hazard assessment (Johnson et al., 2013).

Winds and pressure fields are the major atmospheric forcing in the hurricane system. A synthetic set of 446 storms was created in 2006 for the Joint Surge Study to estimate representative return storm events (USACE 2008a-c). The atmospheric forcing was generated utilizing the Planetary Boundary Layer model (Thompson and Cardone, 1996). For the 2012 Coastal Master Plan, 40 of the 446 production wind fields were simulated for each environmental condition and project analysis. Further details for storm selection as part of the 2012 analysis are described as part of the risk assessment model (Johnson et al., 2013). During the 2017 model improvement period, all 446 storms were simulated on the updated ADCIRC model domain shown in Figure 18. The ADCIRC and UnSWAN model outputs are currently being used to update the selection of production wind fields to be applied as part of the 2017 analysis.

Prior to the production storm simulations for initial and future conditions, the 2012 ADCIRC and UnSWAN models were validated under the initial condition by simulating Hurricanes Gustav and Ike, both making landfall in 2008. These two hurricanes were selected as test cases due to their relatively recent landfall dates, the availability of data assimilated wind and pressure fields and the extensive measurement data available throughout the state. Following the 2017 model improvements and prior to running the 446 storms state wide, the model was validated by simulating Hurricanes Gustav and Ike, as well as Hurricanes Katrina and Rita, both making landfall in 2005.

14.2 Storm Surge and Waves Model Interaction with the ICM and CLARA

As described by Peyronnin et al. (2013), for the 2012 Coastal Master Plan modeling effort, the storm surge and waves model required output directly from the wetland and barrier shoreline morphology models (Couvillion et al., 2013; Hughes et al., 2012) to determine landscape configuration and output from the vegetation model (Visser et al., 2013) to set roughness parameters. For the 2017 Coastal Master Plan, similar outputs will be provided from the ICM. Additionally, the storm surge and waves model provided flood stage time series, maximum wave height, and peak wave period data for use by the risk assessment model (Johnson et al., 2013) in the 2012 analysis and will do the same in 2017. The outputs were applied in the 2012 Coastal Master Plan and will be applied in the 2017 Coastal Master Plan to compute statistical inundation hazard by the risk assessment model at multiple year return periods (e.g., 50-, 100- and 500-year).

Storm surge and wave analyses in the 2012 Coastal Master Plan were completed for with and without action future conditions under three environmental scenarios at year 50: Moderate, Moderate with High Sea Level Rise, and Less Optimistic as described by Peyronnin et al. (2013). For the 2017 analysis, environmental scenarios, as well as multiple time periods including initial conditions, model year 50, and intermediate years, will be analyzed using the storm surge and waves model.

An interaction in the 2017 modeling paradigm that was present during the 2012 Coastal Master Plan is the use of storm surge and waves model data to drive the ICM. Stillwater elevation and wave characteristic model outputs for many of the 446 synthetic storms have been incorporated into the ICM (hydrology and barrier island subroutines) as part of the boundary conditions to define tropical storm event conditions as part of the various environmental scenarios that will be simulated.

For additional information on the storm surge and wave modeling refer to Attachment C3-25 – Storm Surge and Risk Assessment.

15.0 Coastal Louisiana Risk Assessment (CLARA) Model

The Coastal Louisiana Risk Assessment (CLARA) model is a quantitative simulation model of storm surge flood risk developed by a team of researchers at the RAND Corporation for use in the 2012 Coastal Master Plan. The purpose of CLARA was to better understand how future coastal changes could lead to increased risk from storm surge flooding to residents and assets on the Louisiana coast and assess the degree to which proposed projects could reduce this risk. CLARA allowed CPRA to systematically evaluate potential projects for inclusion in the 2012 Coastal Master Plan by estimating their risk reduction benefits. The methods and data used in CLARA, as well as the analysis conducted to support master plan development, are well-described in previously published literature (Fischbach, 2010; Fischbach et al., 2012; Johnson et al., 2013).

This section summarizes a number of improvements made to the CLARA model to support the 2017 Coastal Master Plan. The summary below is adapted from a more complete technical report, Fischbach et al. (2015), which describes in detail the model updates and preliminary analysis conducted to test the revised methods. The detailed report is also included as part of the 2017 Coastal Master Plan documentation (Attachment C3-25 – Storm Surge and Risk Assessment).

This summary first describes the basic structure and functionality of the CLARA model and identifies how inputs from the storm surge and wave analysis are used for coastal flood risk estimation. Significant model improvements for the 2017 analysis are next described, including the goal, methods applied, and key lessons learned. A high-level visual summary of the revised risk analysis process is then presented and described. Finally, selected results from a preliminary investigation using the new model are described, focusing on a comparison to observed flood depth and damage data, sensitivity testing for parametric uncertainty, and an analysis to identify a suitable set of simulated storms to support the 2017 Coastal Master Plan analysis.

15.1 Summary of the CLARA Model

CLARA's structure is based on the principles of quantitative risk analysis, which describe risk as the product of the probability or likelihood of a given event occurring – in this case, the annual probability of storm surge flooding at different depths – and the *consequences* of that event – the damage that results from the flooding. In CLARA, references to flood risk are best understood as flood risk to structures, physical infrastructure, and other local economic assets.

CLARA uses several types of information to estimate flood depths and resulting damage. First are estimated peak storm surge and wave heights. Second are data that characterize the landscape, hurricane protection systems, and assets at risk along the Louisiana coastline. Along the coast, CLARA labels different areas as *unenclosed*, with no levees, floodwalls, or other barriers or with structures that do not fully enclose the population at risk; or *enclosed*, with hurricane protection that fully encloses the area in a ring and creates a "polder."

The structure of the CLARA model is illustrated in Figure 19. In the input preprocessing module, CLARA uses information about the study region and generates flood depth estimates in unenclosed areas and storm hazard conditions for a sample of hypothetical storms. It also records surge and wave conditions along protection structures. In the flood depth module, CLARA estimates flood depths for enclosed areas, with a particular focus on storm surge and wave overtopping and system fragility. CLARA also calculates equilibrium flood depths by distributing water among adjacent enclosed areas. The depth of the flood directly determines the amount of damage that occurs, so flood depths are inputs to the economic module. In this step, CLARA values the assets at risk from flooding and estimates the damage in dollars Fischbach et al. (2012).

Model outputs include summaries of flood depth and damage values at selected annual exceedance probabilities (AEP), which are statistical estimates of the flooding and damage expected to recur with a certain probability in each year. For example, the 1% or 100-year flood exceedance is the flood depth that has a 1% chance of occurring or being exceeded in each year. This is commonly referred to as the 1-in-100 or "100-year flood."

Expected annual damage (EAD) from storm surge flood events is another key model output. EAD is the average storm surge flood damage projected to occur in a single year, taking into account both the effective damage from a given type of storm and the overall likelihood of that storm occurring in a given year. The statistical methods used to estimate AEPs and EAD are based on the joint probability method with optimal sampling (JPM-OS), initially applied for surge risk estimation in coastal Louisiana after the 2005 hurricane season (Resio, 2007). These metrics are generated at each grid point in the model's spatial domain, but may be aggregated to larger spatial units (census tract, parish, etc.) as appropriate.

The basic structure of the CLARA model remains unchanged from 2012. However, substantial improvements have been made to the model since the original 2012 iteration, which is hereafter referred to as "CLARA v1.0." The new version developed for the 2017 Coastal Master Plan is described instead as "CLARA v2.0."

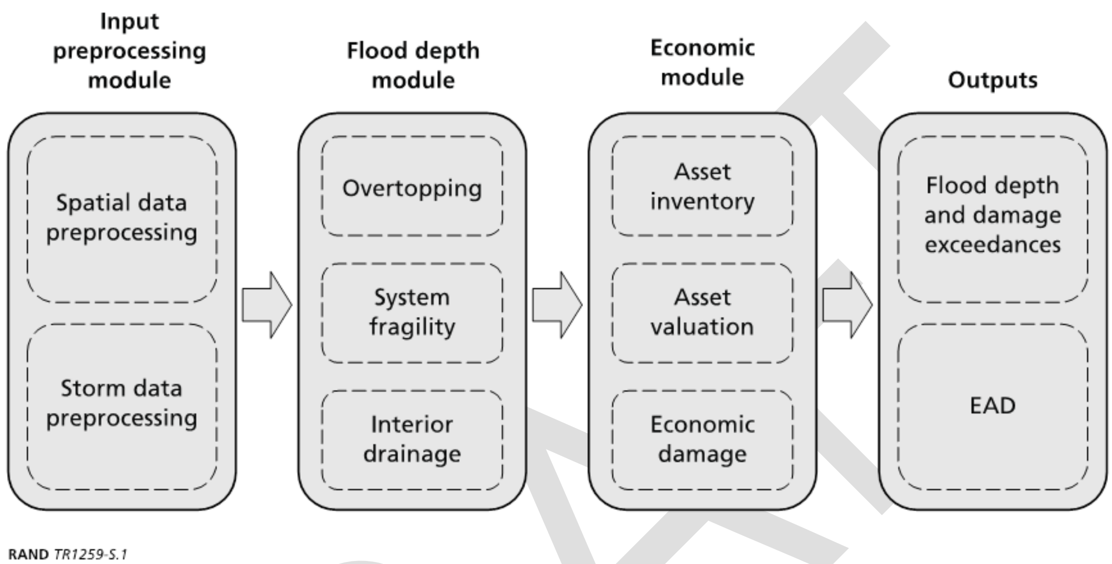

Figure 10: CLARA model structure.

15.2 Model Improvements for 2017

Beginning in October 2013, RAND, CPRA, and The Water Institute worked in partnership to identify high-priority improvements for the CLARA model to implement in preparation for the 2017 Coastal Master Plan analysis. The high-priority needs related to coastal flood risk and damage analysis identified for this effort are summarized below.

15.2.1 Study Region Expanded to Account for a Growing Floodplain

The study region for the 2012 Coastal Master Plan effort was adopted from the 0.1% annual exceedance probability (AEP; or 1-in-1,000 annual chance) floodplain estimated by the U.S. Army Corps of Engineers (USACE) in its 2009 Louisiana Coastal Protection and Restoration (LACPR) report (USACE, 2009). Results from the ADCIRC storm surge analysis for the 2012 Coastal Master Plan, however, showed that the risk of flooding could extend further inland from coastal storms in some future conditions. Accordingly, a key step for 2017 was to expand CLARA's geographic boundaries northward to capture the growing floodplain, including towns such as Gueydan and Kaplan that were partially or completely excluded in the previous iteration.

To expand the study region, the Storm Surge and Wave Team used selected model results from the largest and most intense storm simulations from a set of 446 synthetic storms available for use in coastal Louisiana to identify a maximum plausible surge extent across the coast (assuming a "less optimistic" future landscape scenario 50 years into the future). These results were combined with 2010 U.S. Census urban area boundaries in GIS software to ensure urban areas were left undivided whenever possible, and a new boundary was subsequently identified. Results of this analysis are summarized in Figure 20 below. Portions of coastal Mississippi and Texas were also included (and are shown below) to allow the analysis to consider potential induced flood damage in these neighboring regions with proposed new projects in place.

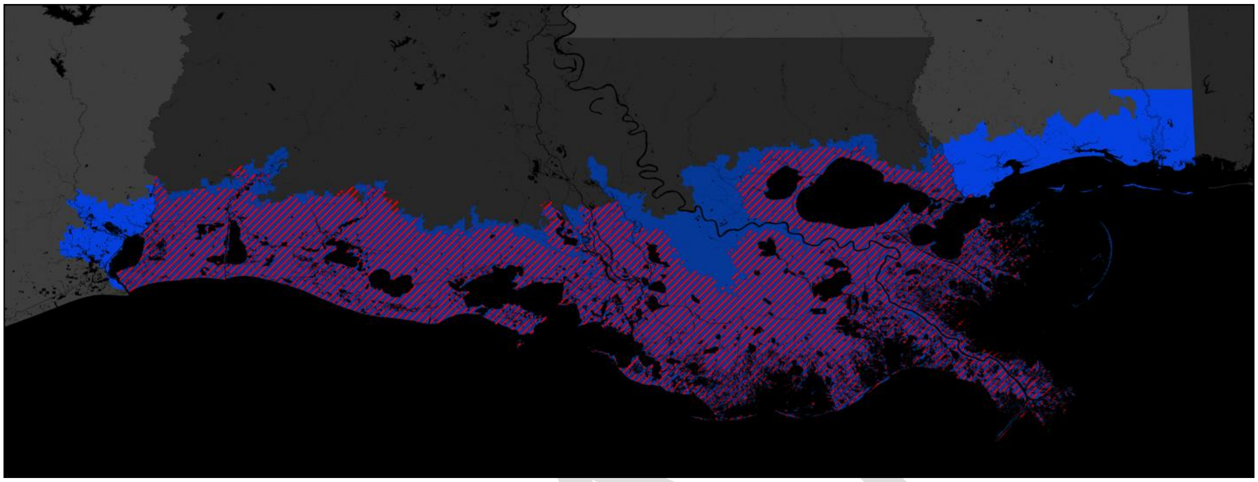

Figure 11: Geospatial domains: CLARA 1.0 (red) and new CLARA v2.0 (blue).

15.2.2 New Spatial Grid Developed to Support Higher Resolution Analysis for Coastal Communities

CLARA v1.0 was first applied to consider proposed risk reduction infrastructure investments, including protection structures such as levees, floodwalls, gates, and pumps, in addition to flood hazard mitigation projects such as elevating or floodproofing individual buildings. The latter project types, sometimes referred to as "nonstructural" risk reduction, were evaluated in a simplified, high-level way in the 2012 Coastal Master Plan analysis. These projects were defined using a handful of representative policy options, including structure elevations, floodproofing, or structure acquisitions. A simple set of decision rules was used to evaluate these project types uniformly in 56 different communities identified in the coastal region.

This high-level approach was useful for comparing the potential benefits of nonstructural investments with the benefits from structural risk reduction projects in a fair and consistent manner. However, after the 2012 analysis, CPRA determined that flood risk and benefits analysis at a higher level of spatial resolution would be helpful in refining nonstructural project strategies in support of the new Flood Risk and Resilience Program. It was also noted that a higher level of spatial resolution would improve flood depth and damage estimates and the subsequent mapping and communication of flood depth results.

To address this need, a new spatial unit of analysis for the flood depth and damage calculations was developed for CLARA v2.0. All aspects of the model were converted to this new grid, including the database of assets at risk. A preliminary analysis of nonstructural benefits and costs also was conducted using initial output at these grid points, with the goal of identifying specific areas with a substantial potential for risk reduction using building elevation, floodproofing, or structure acquisitions.

Spatial units in CLARA were redefined by first updating the economic units from 2000 to 2010 U.S. census blocks, which allows census data from 2010 and onwards to be used in the analysis. Then, a new set of grid points were created by combining the 2010 block centroids with a new grid of regularly-spaced points (RSPs) to ensure a minimum spatial resolution of 1 km x 1 km for the entire coast. The results of this exercise, which produced a total of 90,373 grid points for coastal Louisiana, are shown in Figure 21.

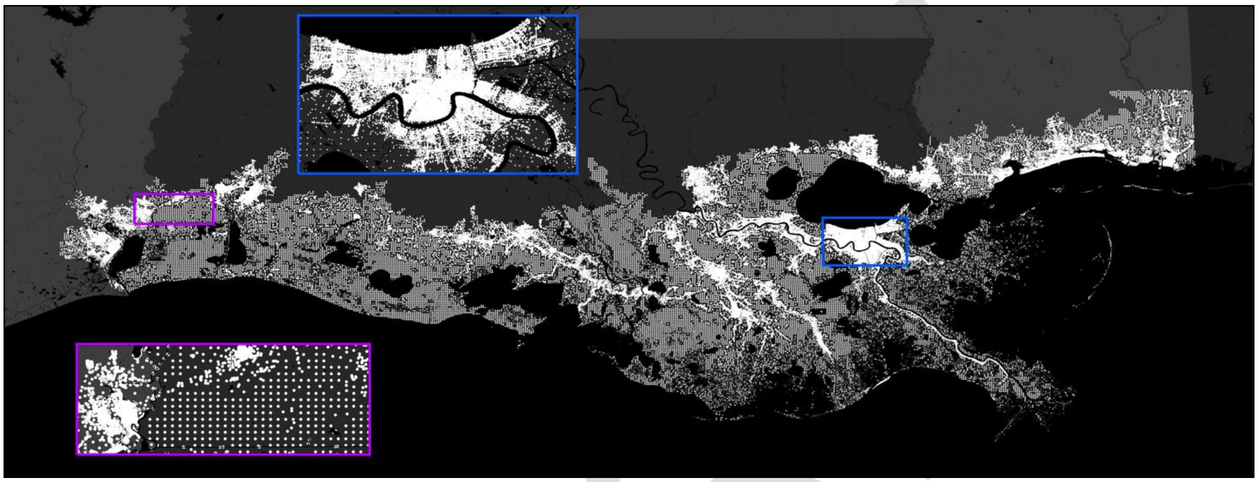

Figure 12: CLARA v2.0 final grid points.

15.2.3 Inventory of Coastal Assets At Risk Expanded and Improved

The inventory of assets at risk in CLARA v1.0 was based largely on data collected by USACE to support its planning in Louisiana subsequent to the devastating 2005 hurricane season. Much of the data describing the coastal population or assets at risk in the floodplain can be dated to the period immediately preceding Hurricanes Katrina and Rita, or is drawn from earlier iterations of the FEMA Hazards-US (Hazus) Multi-hazard model (FEMA, 2011) or the 2000 U.S. Census. In addition, the 2012 Coastal Master Plan analysis did not include data on some key classes of coastal assets, such as power plants, refineries, ports, or other types of critical infrastructure.

For 2017, the database of assets at risk was updated with additional and more recent data identified subsequent to 2012. These updates draw from parcel-level building inventories developed for recent studies and made available by USACE, as well as from a federal infrastructure dataset made available to the state to support its long-term disaster resilience planning.

Figure 22 summarizes the value of assets at risk across each major asset category in initial conditions, comparing the asset databases used by CLARA v1.0 and v2.0 for grid points in coastal Louisiana. Asset values at risk in CLARA are approximately 20-65% greater than in CLARA v1.0 due to the expanded study region, five years of additional growth in the baseline inventory, and improved inventory data that better captures the coast's recovery and redevelopment after the 2005 hurricane season.

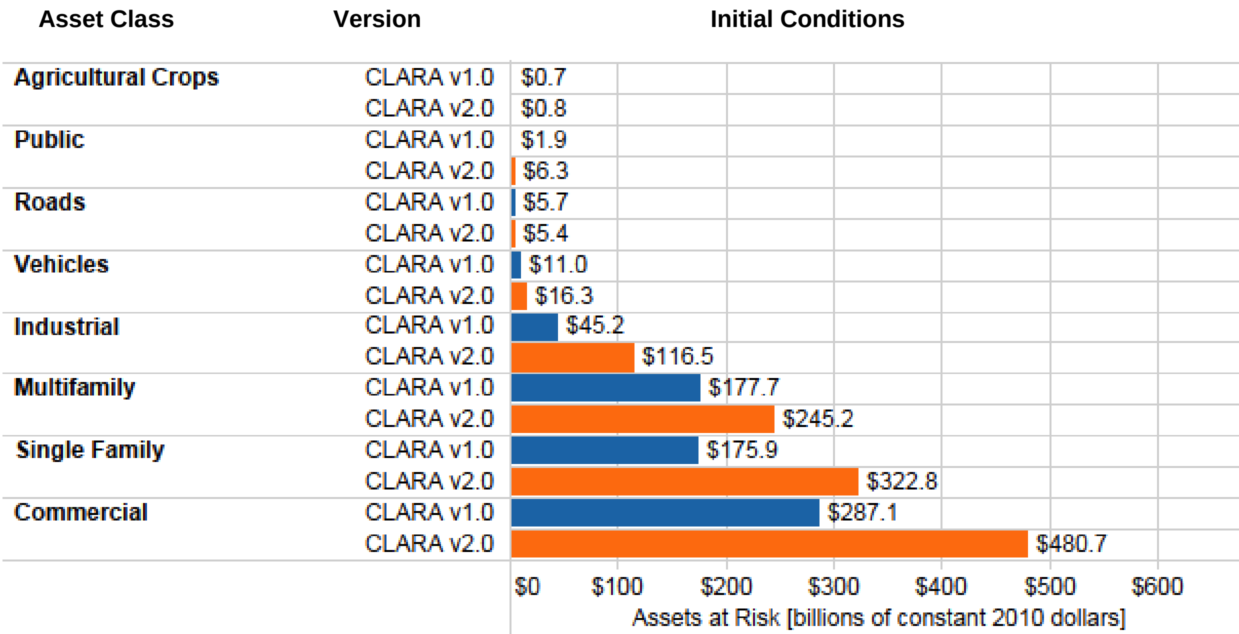

Figure 13: Assets at risk by asset class from CLARA v1.0 versus v2.0, initial conditions (2015).

15.2.4 Scenario Approach of Levee and Floodwall Fragility Improved Based on Recent Research

For the 2012 Coastal Master Plan analysis, CLARA v1.0 used a simplified model to estimate the probability that levees, floodwalls, and other protection structures might fail when faced with increasingly severe storm surge and waves. This approach was based on work done by USACE for the Interagency Performance Evaluation Taskforce (IPET) Risk and Reliability study (IPET, 2009). Since that time, additional studies have been completed on other protection systems or structures in the Louisiana coastal area, including Larose to Golden Meadow (USACE, 2013b), Morganza to the Gulf (MTTG; USACE, 2013a), and the New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS) armoring study (USACE Task Force Hope, 2013), all of which applied different assumptions and approaches to account for the additional risk introduced by potential structure failures. Based on this recent literature, CLARA's assumptions about protection system characteristics and the approach to estimating failure probabilities in CLARA v2.0 were revised, adding scenario uncertainty related to structure fragility to account for the continued lack of scientific consensus on this topic.

Specifically, a new set of fragility curves has been developed which predict the probability of breaches as a function of overtopping rates. A "Low" and "High" fragility curve has been added using assumptions from the MTTG study and the IPET study, respectively, for a total of four fragility curves which can be run. The IPET Low and High options vary in their assumptions about characteristic reach lengths: a shorter characteristic length subdivides levee reaches into a greater number of independent units, which leads to a greater chance of failure for each reach. The MTTG Low and High scenarios, alternately, use the same reach length but make different assumptions about how fragility curves are normalized for each characteristic reach length from the recent USACE estimates. A "No Fragility" overtopping-only case can also be run, as in prior versions.

15.2.5 Parametric Uncertainty Incorporated info Flood Depth Estimates

CLARA v1.0 was developed to address uncertainty from key external drivers looking out 50 years into the future, including sea level rise, coastal land subsidence rates, and future coastal economic growth, none of which could or can be reasonably assigned likelihoods. The 2012 approach used scenario analysis to capture the range of plausible outcomes from these drivers, but for any given scenario, the results calculated by CLARA v1.0 were deterministic (with the exception of a simulation of breaching due to failure of protection system features).

Given the number of steps, volume of input data, and overall complexity of the flood depth and damage calculations in CLARA, there are a variety of additional model uncertainties that were not captured in the scenario analysis, but that could be addressed through probabilistic uncertainty methods. Such methods could be used to estimate how parametric uncertainty propagates and expands throughout the modeling steps, which is especially significant for flood risk assessment because CLARA relies directly on outputs from other systems models.

For CLARA v2.0, a new approach was developed and implemented for quantifying parametric uncertainty – captured using estimates of model variance and reported using statistical confidence intervals – surrounding flood risk estimates. The new parametric uncertainty methods for CLARA v2.0 were designed to directly incorporate “upstream” estimates of uncertainty in the final flood depth estimates in addition to other sources of flood hazard and flood depth uncertainty. However, parametric uncertainty related specifically to asset exposure and structure damage calculations is not yet incorporated into CLARA v2.0. The parametric uncertainty approach is summarized in a subsequent section below along with selected test results.

15.3 Comparison with Hurricane Isaac

Much of the CLARA risk estimation approach cannot be separately calibrated or validated using observed historical data because the model produces statistical projections of flood depth and damage risk spanning a wide range of plausible events. However, some portions of the model, such as flood depth estimates from a single simulated storm, can be compared to past storm outcomes. Hurricane Isaac, which made landfall in Louisiana in August 2012, presented a unique opportunity to make such a comparison, as it affected protection systems around New Orleans and Plaquemines Parish that were nearly identical to how they are represented in CLARA’s current (initial) system condition (2015). This portion of the investigation therefore included a comparison between data gathered during and after Hurricane Isaac and CLARA’s economic asset database, response surface model, interior flood model, and damage calculations.

Hurricane Isaac made two separate landfalls on the Louisiana coast in late August 2012. Isaac was a storm with unique characteristics that present challenges for fitting it into CLARA’s JPM-OS statistical framework. On crossing 29.5 degrees north latitude, Isaac had a radius of maximum wind speed value of 30 nautical miles, a forward velocity of 4 knots, a central pressure of 973 mb, and a landfall angle of 41 degrees west of north. These values are on the extreme end or outside the range of parameters captured by synthetic storms in the currently available 446-storm JPM-OS suite. For instance, the majority of storms in the existing suite have a forward velocity of 11 knots, whereas the slowest storms move at 6 knots.

This analysis, described in detail in the full report, included the following comparisons:

1. The number of residential structures in Plaquemines Parish, by municipality, to the corresponding assets in the CLARA economic database;
2. Peak flood depths, surge elevations, and high-water marks experienced during Isaac in unenclosed areas, to the flood depths predicted by CLARA's response surface model for a synthetic storm with "Isaac-like" storm parameters (a synthetic storm with JPM-OS parameters set to those listed above);
3. Flood depths in enclosed areas from the "Isaac-like" synthetic storm to the flood depths experienced behind the Plaquemines and HSDRRS protection systems; and
4. A comparison of damage to residential assets from Hurricane Isaac to the damage produced by running the Isaac-like synthetic storm through CLARA.

The results of the comparison with Hurricane Isaac were ultimately of mixed utility. Ideally, a comparison to observed depths and damage from this event would build on a high-quality hindcast of the storm using ADCIRC and SWAN. But a reliable, accurate windfield model for the storm has not yet been produced and was not available for the analysis. As a result, high-resolution storm surge and wave simulations were not able to reproduce the storm's observed stillwater elevations and wave heights.

Instead, this comparison used an "Isaac-like" storm drawn from the JPM-OS framework rather than a direct reconstruction using ADCIRC as a next best alternative. This approach produced some insight but also had limitations, however, because currently available JPM-OS storms do not include a storm with Hurricane Isaac's unique characteristics and predicted depths did not match up with observed flooding in some locations.

A summary of the key findings and conclusions from the Isaac comparison exercises is given below. For more information, please see Attachment C3-25 – Storm Surge and Risk Assessment.

- Data quality in CLARA's inventory of economic assets is good: housing units in Plaquemines Parish, for example, are within 2% of reported values, and discrepancies between named communities in the parish are consistent with continuation of settlement trends observed in the last decade.
- Simulated surge elevations from synthetic storms based on the parameters of real, observed storms like Hurricane Isaac are of mixed quality and utility. Further, evaluation of synthetic storm performance in this regard is made difficult by the small number of monitoring stations for and their typical proximity to levee systems.
- Predicted overtopping and flooding in enclosed areas coincided with observed locations during Hurricane Isaac. CLARA calculated that levee failures were likely where none actually occurred, though this had little impact on modeled flood depths within the polders due to the volume of overtopping observed.
- Differences in economic damage assessments were primarily due to differences in the predicted extent of flooding.

15.4 Flood Depth Uncertainty

CLARA's estimates of flood depths incorporate both *aleatory uncertainty*, defined as the inherent and irreducible randomness of some systems or natural processes, and *epistemic uncertainty*, defined as uncertainty due to incomplete knowledge or data regarding the function or relationships in a given system. Uncertainty in CLARA is addressed through the use of three key approaches: (1) Monte Carlo simulation that impacts flooding on an individual-storm level, (2) resampling to generate confidence bounds around the exceedance curves summarizing the distribution of possible flood responses, and (3) scenarios designed to capture the variation due to deep uncertainty that impacts the flood response from all storms. Monte Carlo simulation is applied to estimate both aleatory and epistemic uncertainty at different points in the model. Resampling techniques and scenarios are used to characterize epistemic uncertainty. Table 15 summarizes sources of uncertainty in estimates of coastal flood depths that are addressed in CLARA v2.0.

Table 5: Sources of flood depth uncertainty addressed by CLARA.

Source of Uncertainty	Type of Uncertainty	CLARA Uncertainty Approach
Future state of the coastal landscape: sea level rise, subsidence, etc.	Deep	Scenario analysis
Future storm characteristics: changes to storm frequency, distribution of intensity, etc.	Deep	Scenario analysis
Variability in storm event characteristics	Aleatory	JPM-OS, parametric
Limited historical record of storms	Epistemic	Parametric, bootstrap sampling
Variability in surge and wave responses, given storm characteristics	Aleatory and Epistemic	JPM-OS, parametric
Limited observations of past surge and wave responses, given storm characteristics	Epistemic	Parametric
Impact of the chosen synthetic storm sample on exceedance estimates	Epistemic	*A posteriori* analysis
Impact of the chosen Monte Carlo and bootstrapping sample sizes on exceedance estimates	Epistemic	*A posteriori* analysis
Unknown geospatial correlations in surge and wave responses	Epistemic	Parametric, Monte Carlo simulation
Noise in ground elevation measurements	Epistemic	Parametric
Noise in input model (ADCIRC, UnSWAN) results	Aleatory	Parametric
Stochastic nature of levee and floodwall failure	Aleatory	Monte Carlo simulation
Incomplete understanding of levee and floodwall fragility	Epistemic	Scenario analysis
Variability in breach characteristics and failure consequences	Epistemic	Scenario analysis
Performance of pumping systems	Deep	Scenario analysis

Parametric uncertainties in individual storm results are incorporated into probability distributions representing the possible outcomes, while the model samples from the distributions of other parametric uncertainties to generate confidence bounds around the exceedance curves generated by all storms.

For example, the response surface fit on the ADCIRC and UnSWAN storm outputs is used to predict not only a mean surge and wave response for each synthetic storm, but also standard errors associated with the predictions. These standard errors are used to create multiple versions of each synthetic storm corresponding to different quantile values in the predicted distribution; a Markov chain Monte Carlo method is used to account for geospatial correlation in surge and wave behavior at nearby points along a protection system boundary.

Measurement error in digital elevation models stemming from noise in LiDAR datasets or uncertainty in predicted morphology is accounted for when converting calculated surge elevations and wave heights to flood depths. The brief record of observed historical storms has been leveraged through bootstrap sampling to produce uncertainty in the relative likelihood of synthetic storms with different characteristics, and this is reflected in the confidence bounds placed around estimates of flood depth exceedances. A detailed description of how these methods were incorporated can be found in Fischbach et al. (2015).

Selected results from the test-level analysis conducted to support CLARA model improvement and parametric uncertainty methods development are shown below. These results were created from a 446-storm set for initial conditions and in the Year 50 Less Optimistic future without action (FWOA) scenario, which was adopted for this purpose from the 2012 Coastal Master Plan analysis (CPRA, 2012b). Parametric uncertainty is represented with 10th, 50th, and 90th percentile results by interval. These results provide a snapshot of the testing results only, and are intended to give the reader a sense of the variation in results across the new parametric uncertainty calculations and CLARA v2.0's revised fragility scenarios.

Figure 14 shows a map of 1 percent AEP (100-year) flood depths in unenclosed areas of the coast 50 years into the future in one scenario. The figure shows how the 100-year depth results vary across CLARA's new 10th, 50th, and 90th percentile estimates, with each pane showing one percentile outcome.

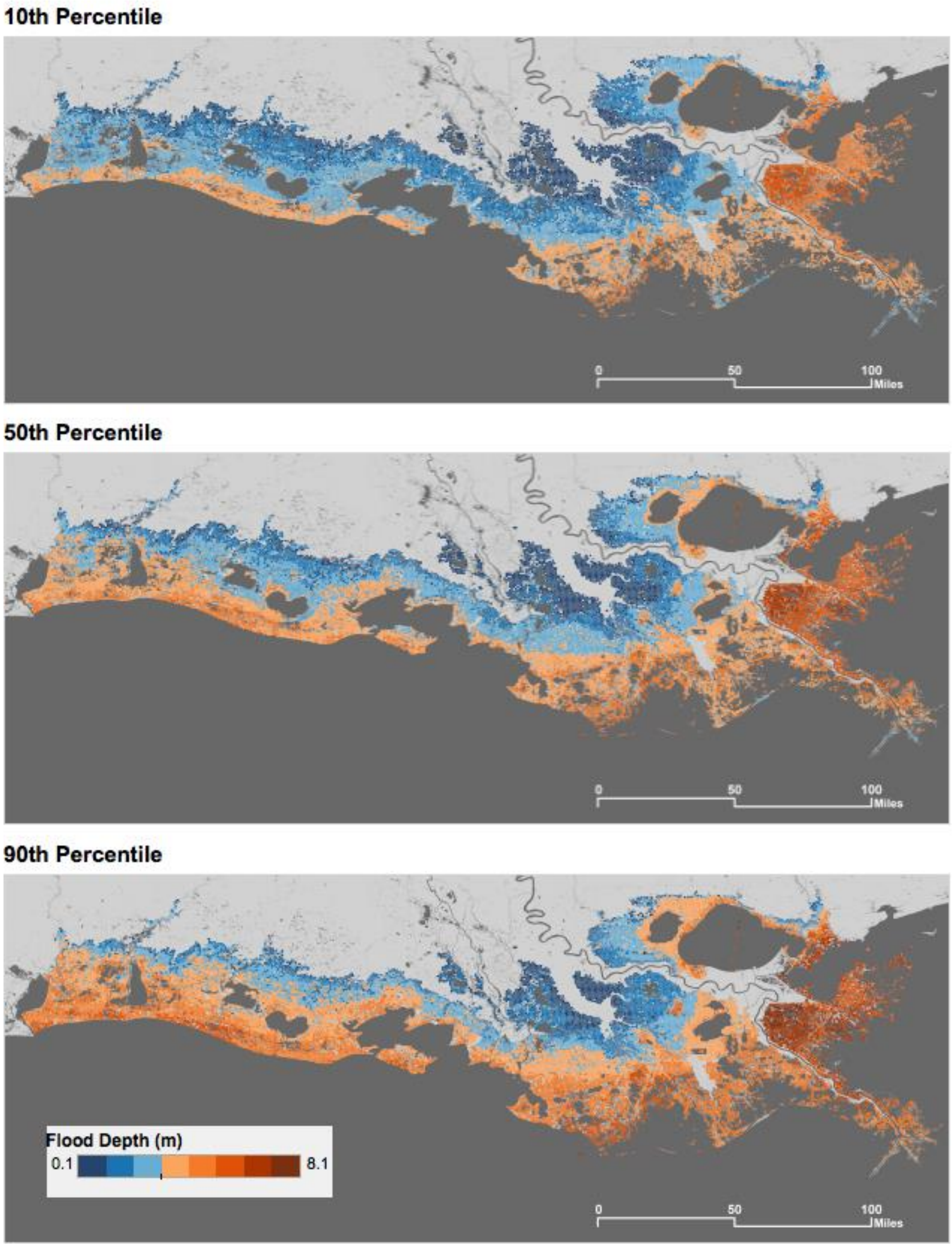

Figure 14: 100-year flood depths by grid point, year 50 less optimistic scenario.

Figure 24 shows damage estimates from CLARA v2.0, in terms of EAD. EAD is summarized in initial conditions (left pane) and in the Year 50 FWOA Less Optimistic scenario (right pane) in two different fragility scenarios, bracketing the most optimistic (IPET Low) and most pessimistic (MTTG High) approaches. The barplots are stacked to show the relative contribution from each asset class at the 50th percentile, with commercial, industrial, and single family residential assets contributing the majority of damage across cases. Vertical lines show the range of EAD results from the 10th to the 90th percentile across the parametric uncertainty range. Similar to the results observed during the 2012 analysis, this shows the dramatic increase in EAD that could occur over the next 50 years, as well as the range of outcomes observed across the new parametric uncertainty estimates.

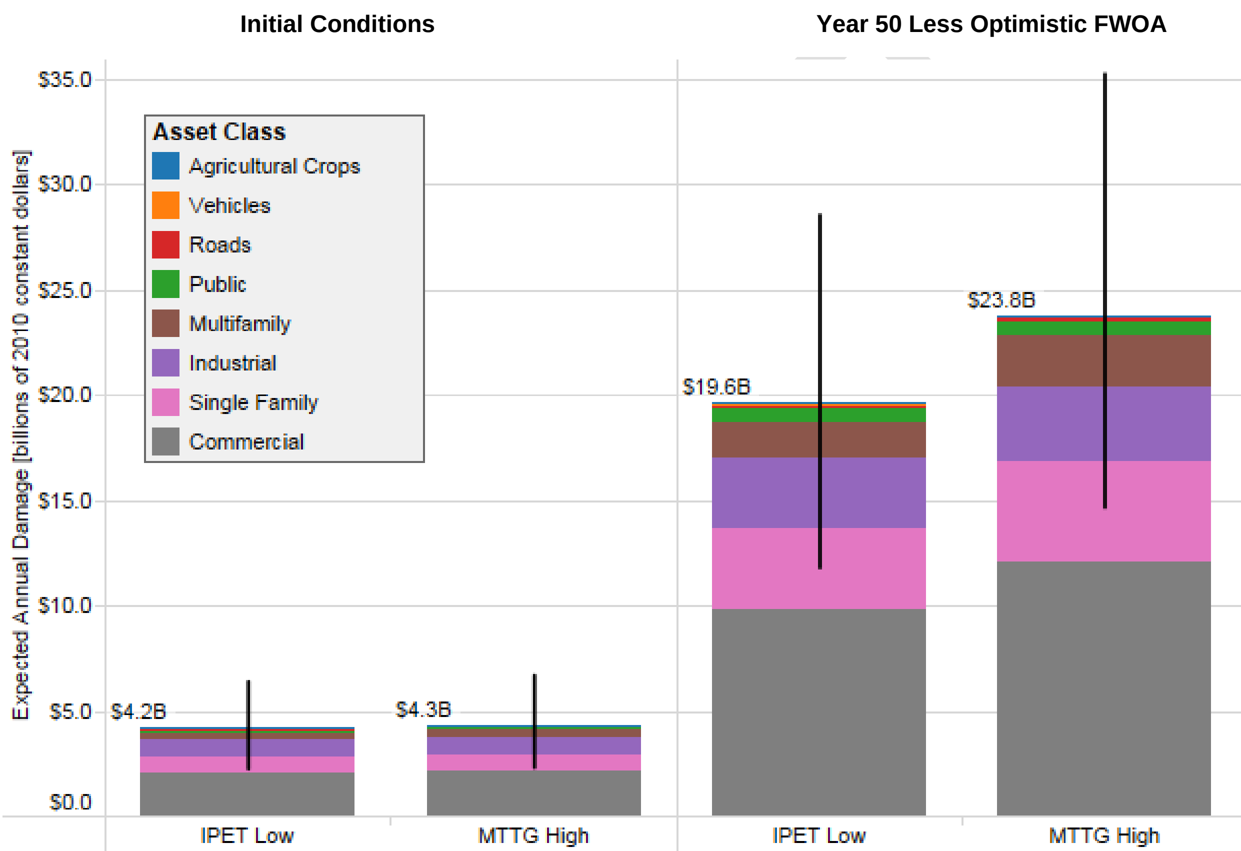

Figure 15: Coast wide EAD in two fragility scenarios, all percentiles, initial and less optimistic year 50 FWOA conditions (billions of 2010 constant dollars).

15.5 Storm Selection Analysis

A key goal to address using the revised CLARA v2.0 model and new parametric uncertainty approach was to better understand the potential tradeoffs CPRA should consider when using a smaller subset of tropical storms (referred to herein as storms) as a training sample for its statistical analysis of flood depths and damage. Fischbach et al. (2012) describe an initial evaluation of potential bias – comparing the subset of 40 storms chosen for the 2012 Coastal Master Plan analysis to a larger set of storms – but this evaluation still relied on a relatively small set to compare against (154 storms), and could not account for the additional uncertainty introduced when reducing the sample size.

To support the 2017 Coastal Master Plan analysis, a more thorough investigation was conducted to consider the tradeoffs associated with smaller subsets of storms. The first step was to conduct an initial screening by comparing a relatively large number of plausible subsets in selected geographic regions of the coast. Subsets were formed by eliminating storms from the full 446-storm set in ways intended to introduce minimal bias. For example, some subsets consist only of storms with a forward velocity of 11 knots, excluding storms from the 446-storm set with faster or slower progression. Other sets eliminate storms that follow “off-angle” tracks, or they may only include storms with minimum central pressures of 960 mb or lower.

Based on the preliminary screening and further input from CPRA, a limited number of storm subsets were then evaluated using the complete CLARA v2.0 depth and damage models for all areas of the coast. The performance of each storm subset was evaluated by estimating bias in predicted flood depths - comparing results from each subset against the outcomes from the full 446-storm reference set (Set 1 in Table 16). The estimated standard errors associated with these exceedance estimates were also compared. The storm subsets tested in this analysis, including number of storms and a description of key characteristics, are shown in Table 16 below.

Table 6: Characteristics of storm sets selected for investigation.

Set	Storms	Description
1	446	Reference storm set
2	40	2012 MP storm set: 10 storm tracks, 4 storms per track that vary $\boldsymbol{c_p}$ and $\boldsymbol{r_{max}}$
3	60	2012 MP storm set expanded to 5 storms per track that vary $\boldsymbol{c_p}$ and $\boldsymbol{r_{max}}$, plus storms with 975 mb $\boldsymbol{c_p}$ and central values for $\boldsymbol{r_{max}}$
4	90	2012 MP storm set expanded to 9 storms per track that vary $\boldsymbol{c_p}$ and $\boldsymbol{r_{max}}$
5	90	7 storms per track (excludes 1 930 mb and 1 900 mb storm) with 975mb storms using extremal (rather than central) $\boldsymbol{r_{max}}$ values
6	92	Set 3, with 960 mb and 975 mb storms on off-angle tracks only in E1-E4
7	92	Set 3, with 960 mb and 975 mb storms on off-angle tracks only in W3-W4, E1-E2
8	100	All central-angle, primary-track storms with 11-knot $\boldsymbol{v_f}$, plus 975 mb storms with central $\boldsymbol{r_{max}}$
9	110	All central-angle, primary-track storms with 11-knot $\boldsymbol{v_f}$, plus 975 mb storms with extremal $\boldsymbol{r_{max}}$
10	120	All central-angle, primary track storms with 11-knot $\boldsymbol{v_f}$, including 975 mb storms
11	154	Set 4, plus all 960 mb and 975 mb storms on primary, off-angle storm tracks

Figure 25 summarizes the average coast wide 100-year flood depth bias (in terms of root mean squared error or RMSE, y-axis) and coefficient of variation (point size) for each set, plotted against number of storms (x-axis). Colors indicate whether the set includes 975 mb storms, and shape indicates whether off-angle tracks are included. Bias is estimated relative to the flood depth results from Set 1, the reference set.

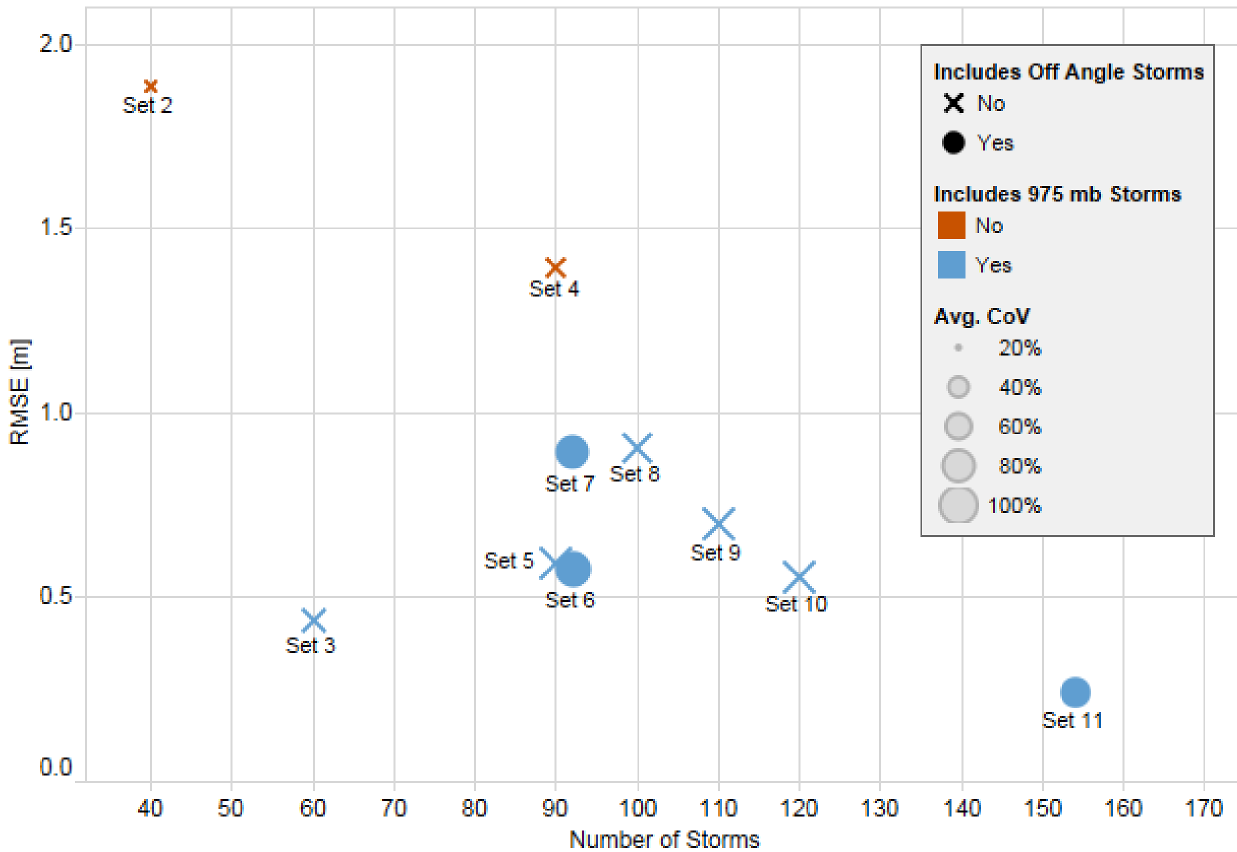

Figure 16: Average coast wide bias and variation by number of storms, 100-year flood depths.

Summary results show that average flood depth bias by point at the 100-year interval varies from less than 0.25 m to nearly 2.0 m, depending on the storm sample. The flood depth results show a tradeoff between the number of storms and the resulting bias when compared with the reference set of 446 storms. Results show that nearly all storm sets tested produce lower bias when compared with the 2012 Coastal Master Plan 40-storm set (Set 2). Substantial improvement is noted when storms with 975 mb central pressure were included, as well as with the addition of off-angle storms in some cases.

Figure 26 shows a coast wide comparison of the storm sets in terms of damage (EAD) bias. The y-axis indicates the bias in coast wide EAD relative to the full 446-storm set (Set 1); the three points for each subset, from bottom to top, represent the bias associated with the 10^{th}, 50^{th}, and 90^{th} percentile values, respectively, of EAD.

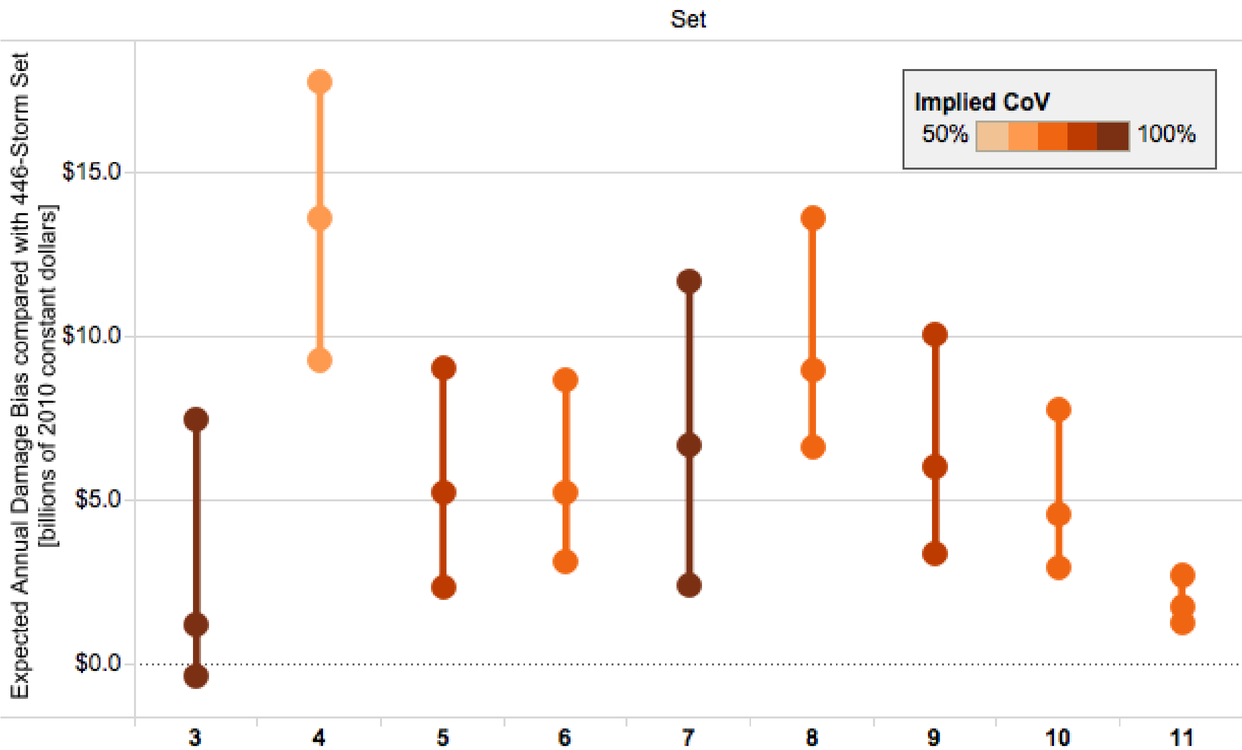

Figure 17: Coast wide bias in terms of expected annual damage (billions of 2010 dollars).

When considering damage bias, results show that Set 11 yields a much smaller variation in bias over the experimental design tested, compared to the other subsets. Considering only sets with fewer than 100 storms, Set 3 is the best performer at the median, but it includes a wider range of results across the parametric distribution and it has performance comparable to Sets 5, 6, and 10 when comparing the 90th percentile results.

Of the subsets tested, Set 11 (154 storms) appears to yield the best balance of results. This set shows relatively low bias compared with the reference set in terms of both flood depth and damage, no concerning spatial patterns of bias, and reasonable performance in enclosed areas (particularly Greater New Orleans; see supporting appendix). This storm set will be used to evaluate and compare coast wide alternatives in the 2017 Coastal Master Plan analysis.

In addition, Set 3 produces the best results among the smaller sets. Given the much smaller number of storms required and relatively unbiased performance at the median, Set 3 will be used to support the comparison of individual structural risk reduction projects during 2017 model production.

16.0 Data Management

16.1 Introduction

As with any effort of this scale, a comprehensive, structured data management plan is crucial to maximize the utility and organization of the various data resources involved in the project. During model execution and output evaluation, data files must be compatible, standardized, easily accessible, and transferable across modeling team members. Short and long-term storage targeting user accessibility of these data sets is also of particular importance along with archival procedures to maintain the data record. This section discusses the various data management components used throughout the 2017 Coastal Master Plan modeling effort.

16.2 File Naming Convention

Large, complex projects, such as the 2017 Coastal Master Plan often consist of a diverse team from multiple agencies and organizations including subject-level subteams. The ease of sharing data across the full project team is a critical need for these types of efforts. A first step for data generation and sharing is the proactive development of a file naming convention, especially when the primary data storage vector is file-based. Building upon the 2012 Coastal Master Plan modeling effort, the file naming convention for the 2017 Coastal Master Plan modeling effort includes requirements to ensure consistency and ease of programming interactions. These requirements include restriction of any use of spaces, use of underscores to delimit components, use of hyphens to delimit elements within a component, only capital letters, padding all components with leading zeros if a numeric component, and trailing capital "X"s if an alphabetic component exists. The file naming convention has twelve filename components: eleven components underscore delimited to the left of the period and one to the right. Specifically, the components of the file naming convention include: 1) Master Plan year; 2) Scenario; 3) Grouping; 4) Coastal Louisiana Risk Assessment model (CLARA) scenario; 5) Uncertainty; 6) Variance; 7) Region, 8) File type; 9) Start year "-" end year; 10) Subroutine; and 11) Parameter (e.g., MP2017_S01_ G001_ C001_U01_ V01_PBB_I_01-05_H_NH4XX.OUT). For more information on the file naming convention, refer to Attachment C3-22 (ICM Development).

16.3 Master Plan Data Server Sandbox

The Master Plan Data Server (MPData Server) Sandbox consists of a large back-end file storage hardware with an attached password-protected web front-end interface. The MPData Server serves as a central repository for task and subtask related documents for each Master Plan team for the 2017 Coastal Master Plan development effort. Differential user access was assigned based on user roles allowing team members the ability to selectively share project information. Following model development and execution, the final 2017 Coastal Master Plan data files will be archived and made accessible through the MPData Server public interface. The MPData server also houses the final versions of the 2012 Coastal Master Plan model outputs.

16.4 Online Code Repository

A source code versioning system is critical to the success of any large-scale programming effort. A code repository serves not only as a central, authoritative source of the latest source code version, but also as a history report, a milestone tracker, and a collaborative tool for geographically dispersed programming teams. For the 2017 Coastal Master Plan modeling effort, a Subversion (SVN) repository was established to host all ICM source code. An account registration and management system was coupled with the CPRA Coastal Information Management System (CIMS) to control read/write access to the code. It was recommended that contributing users interact with the repository by using the TortoiseSVN (http://tortoisesvn.net) client for Windows or the SVN command-line client for Linux (Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.) Users with read-only access may browse the repository either through the web interface or a visual SVN tool, such as the TortoiseSVN repository browser. Upon the completion of the 2017 Coastal Master Plan modeling effort, the code repository will be placed in read-only mode which will "freeze" the 2017 code.

16.5 In-Code Documentation

Source code documentation explains how unique parts of the application work. Doxygen[1] (http://doxygen.org) has been adopted for all in-code documentation in the 2017 Coastal Master Plan ICM source code, with hypertext markup language as the output format. Doxygen is a tool that converts in-code comments into compiled reports in several formats. By using the HTML report format, which can be viewed in any modern web browser, programmers can tag their code using the <...> format, where "…" are HTML-specific tags. In order to prevent the HTML pages from becoming out-of-date, a nightly build tool was created to automatically retrieve the most recent version of the code from SVN, run the Doxygen tool, and publish the newly-created HTML pages on the MPData Server website.

16.6 Production Data Sharing with Secure File Transfer Server (sFTP)

The 2017 Coastal Master Plan models are expected to generate at least 200 terabytes of data across hundreds model simulations. Since model deployment is iterative (i.e., subsequent models require other model results as inputs), a large server resource is needed. The geographically dispersed nature of the modeling teams (e.g., Lafayette, Baton Rouge, New Orleans, and out of state) and the semi-automated nature of the model runs require a secure internet accessible resource supporting functionality to programmatically upload and download data as needed to support modeling efforts. This need was addressed with a large Secure FTP server attached to a redundant array of independent disks (RAID) ensuring high performance and data protection. This storage resource is expected to peak at approximately 250 terabytes of modeling outputs during production runs and through the quality control process when deciding which runs will be stored long term. It should be noted that over the course of 2017 model runs, approximately 100 terabytes of data were transferred to this server using external drives that were physically delivered from model execution locations to the data center. This was determined to be a more efficient process of large data transfer than electronic transfer via the internet.

All runs needing long-term preservation will ultimately be archived and final master plan runs will be visualized and available for download in the next generation CPRA Master Plan Data Viewer (http://cims.coastal.la.gov/masterplan/) and (or) the main CIMS Spatial Viewer (http://cims.coastal.la.gov/MapHome.aspx).

16.7 Data Quality Assurance and Quality Control Process

Some degree of error is a reality for any data intensive effort. A QA/QC process helps ensure confidence in the final data product. All model outputs were subjected to various levels of review to confirm accurate execution of the logic and algorithms of the models and to assure proper project implementation where applicable. Numerous checks were performed on modeled variables which varied across the models but included as examples: bar and time series charts which allowed quick review of summary statistics such as minimum/maximum/mean, overview or cross section maps, and tables of strategically developed summary values. Of the hundreds of model runs, a subset of output was directed to reviewers for QA/QC. Details of the review were logged and archived on the sFTP site. For additional information on the QA/QC procedures undertaken by each modeling team, refer to Attachment C4-1 Modeling Quality Assurance and Quality Control.

16.8 Data Storage and Conversion to NetCDF

A data conversion tool, File Watcher and Data Converter (FWDC), was developed to aid in data standardization and the QA/QC process. During the 2012 Coastal Master Plan modeling effort, many of the modeling outputs were converted to the network common data format (NetCDF) file format and viewed with the EverVIEW Data Viewer application (http://www.jem.gov). NetCDF is an open file format with self-describing metadata, designed to store gridded spatiotemporal data, and has many tools and software libraries available. The FWDC converts several of the modeling output formats (e.g., ASCII Grid, GeoTIFF, ERDAS Imagine, and other custom formats) to NetCDF datasets. One benefit of this process is that additional metadata can be embedded within the dataset if the source files conform to the File Naming Convention, and multiple time steps can be collated together (e.g., 50 modeling years files included in one NetCDF).

This first phase of FWDC development consisted of an automated tool that scanned the file system every six hours for new or updated modeling outputs. If new or updated files were detected, they would be checked to ensure that they conform to the file naming convention. The FWDC would perform minor renaming changes as necessary, and then begin the process of converting and collating (over the time dimension) the modeling files, and then compressing them to a single zip archive.

The second phase of FWDC development was necessary to handle a change in how often and how much modeling data were present. Through several data transfers, large amounts of modeling data became available for conversion, pushing the limits of the "periodically scan, then update" design of the FWDC. The application was redesigned to run semi-automated in a "scan once, convert" fashion. For the redesign, each scan was started manually and pointed to a single modeling scenario folder, and any group of files that has not been converted is queued for conversion and automatically processed as resources are available.

16.9 Future Master Plan Data Management Suggestions

The following are suggestions for future improvements from the perspective of the data management team:

1. **Forced adherence to the file naming convention through deletion of non-compliant data files.**

    The file naming convention has seen growth and maturation over the years and has a good mix of structure and flexibility. Forcing compliance helps the programmers from the various modeling teams know in advance how data files will be named and therefore automate their models internal data movement logistics for efficiency. Since growth and change is expected, this should be addressed as one of the first processes for future efforts.

2. **Consider adopting NetCDF as the primary data storage container and coding models to interact directly from and into a NetCDF file.**

    This would eliminate the need to convert data from various formats and would facilitate service-enabling all modeling outputs using the Unidata Thematic Real-Time Environmental Distributed Data Services (THREDDS) server (http://www.unidata.ucar.edu/software/thredds/current/tds/). Additionally, using NetCDF with THREDDS opens the opportunity to automate on the server some data analysis such as generating scenario differences or assessing scenario change over time.

3. **Consider using a shared, remotely accessible computational environment.**
The cloud offers some very compelling options which address many of the challenges that existed in both the 2012 and 2017 Coastal Master Plan efforts. A shared, remotely accessible cloud platform could be scaled up or down very quickly to match computational and storage needs of a model run. This shared storage would eliminate the need for sFTP and help reduce data transfer load. Most cloud resources are sold as "on-demand" or "pay as you go." This gives the user the flexibility to turn resources on or off as needed. Additionally, cloud resources could result in a modeling execution platform with tremendous computational power resulting in extremely fast run-times that can be powered off when not in use and completely abandoned after scenario runs are completed.

17.0 References

Arcement, G.J. and Schneider V.R. (1989). Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains (p. 38). Denver, CO: U.S. Geological Survey Water-Supply Paper 2339.

Baltz, D. (2012a). Brown shrimp (juvenile) habitat suitability index (Appendix D-16). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.14). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Baltz, D. (2012b). White shrimp (juvenile) habitat suitability index (Appendix D-17). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.13). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Baltz, D. (2012c). Spotted seatrout (juvenile) habitat suitability index (Appendix D-18). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p. 14). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Christiansen, T., Wiberg, P.L. and Milligan, T.G. (2000). Flow and sediment transport on a tidal salt marsh surface. *Estuarine, Coastal and Shelf Science 50* (pp.315-331).

Christensen, V., Coll, M., Steenbeek, J., Buszowski, J., Chagaris, D. and Walters, C.J. (2014). Representing variable habitat quality in a spatial food web model. *Ecosystems 17* (pp. 1397-1412).

Christensen, V. and Pauly, D. (1992). Ecopath II—a software for balancing steady-state ecosystem
models and calculating network characteristics. *Ecological Modelling* (pp.169-185).

Christensen, V. and Walters, C.J. (2004). Ecopath with Ecosim: methods, capabilities and limitations. *Ecological Modelling 172* (pp. 109-139).

Christensen, V., Walters, C.J, Pauly, D. and Forrest, R. (2008). Ecopath with Ecosim version 6 user Guide (p. 235). University of British Columbia, Vancouver: Fisheries Centre.

Coastal Protection and Restoration Authority of Louisiana. (2012). Louisiana's Comprehensive

Master Plan for a Sustainable Coast. Baton Rouge, LA: Coastal Protection and Restoration Authority of Louisiana.

Cobell, Z., Zhao, H., Roberts, H.J., Clark, F.R. and Zou, S. (2013). Surge and wave modeling for the Louisiana 2012 Coastal Master Plan. In: N. Peyronnin and D. Reed (Eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis, Journal of Coastal Research, Special Issue No. 67* (pp. 88–108).

Couvillion, B.R., Steyer, G.D., Wang, H., Beck, H.J. and Rybczyk, J.M. (2013). Forecasting the effects of coastal protection and restoration projects on wetland morphology in coastal Louisiana under multiple environmental uncertainty scenarios. In: N. Peyronnin and D. Reed (Eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis. Journal of Coastal Research, Special Issue, No. 67* (pp. 29–50).

Dietrich, J.C., Westerink, J.J., Kennedy, A.B., Smith, J.M., Jensen, R., Zijlema, M., Holthuijsen, L.H., Dawson, C., Luettich, R.A., Jr., Powell, M.D., Cardone, V.J., Cox, A.T., Stone, G.W., Pourtaheri, H., Hope, M.E., Tanaka, S., Westerink, L.G., Westerink, H.J. and Cobell, Z. (2011). Hurricane Gustav (2008) waves and storm surge: hindcast, synoptic analysis and validation in southern Louisiana. *Monthly Weather Review, 139(8)* (pp. 2488–2522).

Federal Emergency Management Agency [FEMA] (2005). HAZUS: Hazard Loss Estimation Methodology. http://www.fema.gov/hazus.

FEMA. (2011). Hazus®-MH 2.0 Multi-hazard Loss Estimation Methodology Technical Manual: Flood Model. Washington, D.C.: Department of Homeland Security.

Fischbach, J. R. (2010). Managing New Orleans Flood Risk in an Uncertain Future Using Non-Structural Risk Mitigation. Santa Monica, CA: RAND Corporation, RGSD-262.

Fischbach, J. R., Johnson, D. R., Kuhn, K., Pollard, M., Stelzner, C., Costello, R., . . . Cobell, Z. (2015). 2017 Coastal Master Plan: Model Improvement Plan, Storm Surge and Risk Assessment Improvements (Subtask 4.9). Version III. (pp. 212). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Fischbach, J. R., Johnson, D. R., Ortiz, D. S., Bryant, B. P., Hoover, M. and Ostwald, J. (2012). Coastal Louisiana Risk Assessment Model: Technical Description and 2012 Coastal Master Plan Analysis Results. Santa Monica, CA: RAND Corporation, TR-1259-CPRA.

Hubertz, J.M. and Brooks, R.M. (1992). Verification of the Gulf of Mexico hindcast wave information. *Wave Information Studies (WIS) Report 28* (p. 35) Washington, D.C.: Department of the Army, US Army Corps of Engineers.

Hughes, Z., Weathers, G., Georgiou, I., FitzGerald, D. and Kulp, M. (2012). Appendix D-3: Barrier Shoreline Morphology Technical Report. In *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge, LA: Coastal Protection and Restoration Authority.

Interagency Performance Evaluation Taskforce (IPET). (2009). Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Vol. VIII: Engineering and Operational Risk and Reliability Analysis: U.S. Army Corps of Engineers.

Johnson, D. R., Fischbach, J. R. and Ortiz, D. S. (2013). Estimating Surge-Based Flood Risk with the

Coastal Louisiana Risk Assessment Model. Journal of Coastal Research, (Special Issue 67 – Louisiana's 2012 Coastal Master Plan Technical Analysis), 109-126.

Kaller, M.D. (2012). Largemouth bass habitat suitability index (Appendix D-9). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p. 20). Baton Rouge, Louisiana: Coastal Protection and Restoration Authority.

Katner, A., Ogunyinka,, E., Sun, M.H., Soileau, S., Lavergne, D., Dugas, D. and Suffet., M. (2001). Fishing, fish consumption and advisory awareness among Louisiana's recreational fisheries. *Environmental Research 111* (pp. 1037-1045).

Leberg, P.L. (2012a). Gadwall habitat suitability index (Appendix D- 7). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.11). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Leberg, P.L. (2012b). Mottled duck habitat suitability index (Appendix D-10). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.12). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Leberg, P.L. (2012c). Green-winged teal habitat suitability index (Appendix D-8). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.11). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Leberg, P.L. (2012d). Neotropical migrants habitat suitability index (Appendix D-12). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.12). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Leberg, P.L. (2012e). Roseate spoonbill habitat suitability index (Appendix D-15). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.13). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Meselhe, E., McCorquodale, J. A., Sheldon, J., Dortch, M., Brown, S., Davis, M., Wang, Z., Elkan, P. and Schindler, J. (2012). Eco-hydrology model technical report (Appendix D-1). In *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge, LA: Coastal Protection and Restoration Authority.

Nyman, J.A. (2012a). American alligator habitat suitability index (Appendix D-8). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.18). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Nyman, J.A. (2012b). Muskrat habitat suitability index (Appendix D-11). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.13). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Nyman, J.A. (2012c). River otter habitat suitability index (Appendix D-14). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.14). Baton Rouge, LA: Coastal Protection and Restoration Authority.

NOAA. (2014). Annual Commercial Landing Statistics, Retrieved on May 14, 2014. From. http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index.

Peyronnin, N., Green, M., Parsons Richards, C., Owens, A., Reed, D., Groves, D., Chamberlain, J., Rhinehart, K. and Belhadjali, K. (2013). Louisiana's 2012 Coastal Master Plan: Overview of a Science Based and Publicly-Informed Decision Making Process. In: N. Peyronnin and D. Reed (Eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis. Journal of Coastal Research, Special Issue No. 67* (pp. 1–15).

Polovina, J.J. (1984). Model of a coral reef ecosystem. *Coral reefs 3* (pp. 1-11).

Resio, D.T. (2007). White Paper on Estimating Hurricane Inundation Probabilities Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Vol. VIII: Engineering and Operational Risk and Reliability Analysis. New Orleans, LA: U.S. Army Corps of Engineers.

Rivera-Monroy, V.H., Branoff, B., Meselhe, E., McCorquodale, A., Dortch, M., Steyer, G.D., Visser, J. and Wang, H. (2013). Landscape-level estimation of nitrogen loss in coastal Louisiana wetlands: potential sinks under different restoration scenarios. In: N.S. Peyronnin and D.J. Reed (Eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis*. *Journal of Coastal Research, Special Issue No. 67*.

Rivera-Monroy, V.H., Teague, K. Swenson, E.M., Barko, J., Dortch, M.S., Justic, D., McCorquodale, J.A., Nestler, J.A. and Twilley, R.R. (2003). Water Quality Module, Chapter 11. In, R.R. Twilley (ed.), Coastal Louisiana Ecosystem Assessment and Restoration (CLEAR) Model of Louisiana Coastal Area (LCA) Comprehensive Ecosystem Restoration Plan. Volume I: Tasks 1-8. Final Report to Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. Contract No. 2511-02-24.

Romaire, R.P. (2012). Crawfish (wild caught) habitat suitability index (Appendix D-6). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.20) . Baton Rouge, LA: Coastal Protection and Restoration Authority.

Soniat, T. (2012). Eastern oyster habitat suitability index (Appendix D-13). In: *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (p.18). Baton Rouge, LA: Coastal Protection and Restoration Authority.

Steenbeek, J., Coll, M., Gurney, L., Mélin, F., Hoepffner, N., Buszowski, J. and Christensen, V. (2013).
Bridging the gap between ecosystem modeling tools and geographic information systems: Driving a food web model with external spatial–temporal data. *Ecological Modelling 263* (pp. 139-151).

Thompson, E.F. and Cardone, V.J. (1996). Practical modeling of hurricane surface wind fields. *Journal of Waterway, Port, Coastal, and Ocean Engineering122[4]* (p. 195–205).

U.S. Army Corps of Engineers (USACE). (2009). Louisiana Coastal Protection and Restoration Technical Report. New Orleans, LA: U.S. Army Corps of Engineers.

USACE (2013a). Final Post Authorization Change Report: Morganza to the
Gulf of Mexico, Louisiana (pp. 122). New Orleans, LA: U.S. Army Corps of Engineers, Louisiana Coastal Protection and Restoration Authority Board, and Terrebonne Levee and Conservation District.

USACE (2013b). Larose to Golden Meadow Hurricane Protection Project Risk Based Benefit Cost Ratio HEC-FDA Analysis. New Orleans, LA.

USACE: Task Force Hope. (2013). Greater New Orleans Hurricane and Storm Damage Risk Reduction System: HSDRRS Resiliency Brief. Retrieved on August 8, 2014. From http://www.slfpae.com/presentations/2013 07 18 - USACE Resiliency.PDF

USACE (2008). Flood insurance study: Southeastern parishes, Louisiana. Intermediate Submission 2: Offshore Water Levels and Waves. Vicksburg, MS.

USACE (2008a). Louisiana Coastal Protection and Restoration Technical Report (p.98). Vicksburg, MS: USACE.

USACE (2008b). Flood Insurance Study: Southeastern Parishes, Louisiana. *Intermediate Submission 2: Offshore Water Levels and Waves* (p.152). Vicksburg, MS: USACE.

USACE (2008c). Flood Insurance Study: Southwestern Parishes, Louisiana. *Intermediate Submission 2* (p. 697). Vicksburg, MS: USACE.

Visser, J.M., Duke-Sylvester, S.M., Carter, J., and Broussard III, W.P. (2013). A computer model to forecast wetland vegetation changes resulting from restoration and protection in coastal Louisiana. In: N. Peyronnin and D. Reed (Eds.), *Louisiana's 2012 Coastal Master Plan Technical Analysis. Journal of Coastal Research, Special Issue, No. 67* (pp. 51-59).

Walters, C., Christensen, V. and Pauly, D. (1997). Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries 7* (pp. 139-172).

Walters, C. and Martell, S. (2004). Fisheries ecology and management. Princeton Univ Pr.

Walters, C., Pauly, D. and Christensen, V. (1999). Ecospace: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. *Ecosystems 2* (pp. 539-554).

Walters, C., Pauly, D., Christensen, V. and Kitchell, J.F. (2000). Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. *Ecosystems 3* (pp. 70-83).

Warren Pinnacle Consulting, Inc. (2012) SLAMM 6.2 Technical Documentation - Sea Level Affecting Marshes Model, Version 6.2 beta. Retrieved from http://warrenpinnacle.com/prof/SLAMM6/SLAMM6.2_Technical_Documentation.pdf

Worm, B., Hilborn, R., Baum, J.K., Branch, T.A., Collie, J.S., Costello, C., Fogarty, M.J., Fulton, E.A., Hutchings, J.A. and Jennings, S. (2009). Rebuilding global fisheries. *Science 325* (pp. 578-585).